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EXPLORING THE

MOON AND MARS

CHOICES FOR THE NATION

J952-72

CONGRESS OF THE UNITED STATES OFFICE OF TECHNOLOGY ASSESSMENT

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Foreword

The United States has always been at the forefront of exploring the planets. U.S. spacecraft have now journeyed near every planet in the solar system but Pluto, the most distant one. Its probes have also landed on the Moon and Mars. *Magellan*, the most recent of U.S. interplanetary voyagers, has been returning thought-provoking, high-resolution radar images of the surface of Venus.

Scientifically, the prospect of returning to the Moon and exploring Mars in greater detail is an exciting one. President George Bush's proposal to establish a permanent lunar base and to send human crews to explore Mars is ambitious and would engage both scientists and engineers in challenging tasks. Yet it also raises a host of issues regarding the appropriate mix of humans and machines, timeliness, and costs of space exploration. This Nation faces a sobering variety of economic, environmental, and technological challenges over the next few decades, all of which will make major demands on the Federal budget and other national assets. Within this context, Congress will have to decide the appropriate pace and direction for the President's space exploration proposal.

This report, the result of an assessment of the potential for automation and robotics technology to assist in the exploration of the Moon and Mars, raises a number of issues related to the goals of the U.S. civilian space program. Among other things, the report discusses how greater attention to automation and robotics technologies could contribute to U.S. space exploration efforts.

In undertaking this report, OTA sought the contributions of a broad spectrum of knowledgeable individuals and organizations. Some provided information, others reviewed drafts. OTA gratefully acknowledges their contributions of time and intellectual effort.

John H Gibbons

JOHN H. GIBBONS
Director

Workshop on the Robotic Exploration of the Moon and Mars, Feb. 20, 1991

Alan Shaw, *Chair*
Manager
International Security and Commerce Program
Office of Technology Assessment

Ronald Brunner
Professor
Department of Political Science
University of Colorado
Boulder, CO

Michael H. Carr
Geologist
United States Geological Survey
Branch of Astrogeology
Menlo Park, CA

Ben Clark
Technical Director
Martin Marietta Corp.
Denver, CO

Lynn Conway
Associate Dean
College of Engineering
University of Michigan
Ann Arbor, MI

Michael Duke
Deputy for Science Lunar and
Mars Exploration Program Office
NASA Johnson Space Center
Houston, TX

Matthew P. Golombek
Research Scientist
Jet Propulsion Laboratory
Pasadena, CA

Noel Hinners
Vice President and Chief Scientist
Civil Space and Communications
Martin Marietta Corp.
Bethesda, MD

Eugene Levy
Chairman
Department of Planetary Science
Lunar and Planetary Laboratory
University of Arizona
Tucson, AZ

Henry Lum
Chief
Information Sciences Division
NASA Ames Research Laboratory
Moffett Field, CA

Carle Pieters
Associate Professor
Department of Geosciences
Brown University
Providence, RI

Paul Spudis
Staff Scientist
Lunar and Planetary Institute
Houston, TX

Alan Stern
Research Scientist
Center for Astrophysics and Space Astronomy
University of Colorado
Boulder, CO

Carol Stoker
Research Scientist
NASA Ames Research Center
Moffett Field, CA

Giulio Varsi
Manager
Space Automation and Robotics Program
Jet Propulsion Laboratory
Pasadena, CA

William L. Whittaker
Director
Field Robotics Laboratory
Carnegie Mellon University
Pittsburgh, PA

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OTA Project Staff – Exploring the Moon and Mars

Lionel S. Johns, *Assistant Director, OTA*
Energy, Materials, and International Security Division

Alan Shaw, *International Security and Commerce Program Manager*

Ray A. Williamson, *Project Director*

Contributor

Victoria Garshnek, Space Policy Institute, George Washington University

Administrative Staff

Jacqueline R. Boykin
Madeline Gross
Louise Staley

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Arnold D. Aldrich
NASA Headquarters
Washington, DC

Dale Andersen
Lockheed Corp.
Washington, DC

Phillip Ballou
Deep Ocean Engineering
San Leandro, CA

Roger Bedard
Jet Propulsion Laboratory
Pasadena, CA

Geoffrey Briggs
Center for Earth and Planetary Studies
National Air and Space Museum
Smithsonian Institution
Washington, DC

Robert Cannon
Department of Aeronautics and Astronautics
Stanford University
Stanford, CA

Leonard David
Space Data Resources and Information
Washington, DC

Kevin Dowling
Robotics Institute
Carnegie Mellon University
Pittsburgh, PA

Terry Finn
NASA Headquarters
Washington, DC

Herbert Frey
NASA Goddard Space Flight Center
Greenbelt, MD

Peter Friedland
Intelligent Systems Research Division
NASA Ames Research Center
Moffett Field, CA

Louis D. Friedman
The Planetary Society
Pasadena, CA

Stephen J. Hoffman
Science Applications International Corp.
Houston, TX

G. Scott Hubbard
NASA Ames Research Center
Moffett Field, CA

Eric Krotkov
The Robotics Institute
Carnegie Mellon University
Pittsburgh, PA

Louis J. Lanzerotti
AT&T Bell Laboratories
Murray Hill, NJ

Paul Lowman
NASA Goddard Space Flight Center
Greenbelt, MD

Michael Malin
Arizona State University
Tempe, AZ

Harry McCain
NASA Goddard Space Flight Center
Greenbelt, MD

Wallace A. McClure
Westminster, CA

Chris McKay
NASA Ames Research Center
Moffett Field, CA

John Menkins
NASA Headquarters
Washington, DC

Lt. Col. Eric Mettala
Defense Advanced Research Projects Agency
U.S. Department of Defense
Washington, DC

David Moore
Congressional Budget Office
Washington, DC

Douglas B. Nash
Jet Propulsion Laboratory
Pasadena, CA

Acknowledgments (continued)

Carl B. Pilcher
NASA Headquarters
Washington, DC

Donna Pivirotto
Jet Propulsion Laboratory
Pasadena, CA

Ian Pryke
European Space Agency
Washington, DC

Don Rea
Mitre Corp.
McLean, VA

Eberhardt Rechtin
University of Southern California
Los Angeles, CA

Sally Ride
California Space Institute
La Jolla, CA

Carl Ruoff
Jet Propulsion Laboratory
Pasadena, CA

Jeffery Rosendahl
NASA Headquarters
Washington, DC

Harrison Schmitt
Albuquerque, NM

David R. Scott
Scott Science and Technology
Los Angeles, CA

Steven Squyres
Cornell University
Ithaca, NY

Delbert Tesar
University of Texas at Austin
Austin, TX

Paul Uhlir
National Research Council
Washington, DC

Jannelle Warren-Findley
Falls Church, VA

Jerry Wasserburg
California Institute of Technology
Pasadena, CA

Dietmar Wurzel
German Aerospace Research Establishment
and German Space Agency
Washington, DC

Maria Zuber
NASA Goddard Space Flight Center
Greenbelt, MD

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Chapter 1
Summary

INTRODUCTION

On July 20, 1989, two decades after the first Apollo landing on the Moon, President George Bush proposed "a long-range, continuing commitment"[1] that would take the United States "back to the Moon...back to stay,"[2] and then on to Mars. The President elaborated further on his vision in May 1990, when he stated, "I am pleased to ... announce a new Age of Exploration, with not only a goal but also a timetable: I believe that before Apollo celebrates the 50th anniversary of its landing on the Moon [2019]—the American flag should be planted on Mars."[3]

In response to the President's proposals, the National Aeronautics and Space Administration (NASA), the Department of Defense (DoD), and the Department of Energy (DOE) have begun work on the Space Exploration Initiative (SEI),[4] an endeavor to plan and implement the human exploration of the Moon and Mars. NASA is the principal implementing agency. The National Science Foundation will participate in a limited way through a joint Antarctic Program, testing technologies and methods for Mars exploration.[5]

Although the SEI is devoted principally to developing and analyzing the steps required for human exploration of the Moon and Mars, NASA's plans for SEI also include robotic science missions: first to gather scientific data[6] prior to a landing by humans, and later as adjuncts to human exploration on the surface.[7] Data from the first set of robotic spacecraft would further scientific studies and assist planners to select the best sites for landing and erecting base camps. The appropriate mix of human and robotic exploration is currently under study by NASA, and by several internal and external advisory groups.[8]

As a result of their concern over the extent and scope of science objectives that can be accomplished within potential NASA appropriations over the next three decades, the Subcommittees on Veterans Administration, Housing and Urban Development, and Independent Agencies of the House and Senate Appropriations Committees asked OTA to examine "whether an unmanned, robotic mission or missions might not be a viable option for us to consider" for scientific study of the Moon and Mars, and in the utilization of physical resources on the two celestial bodies.[9]

This report focuses primarily on the possible roles of automation and robotics (A&R) technologies in the exploration and utilization of the Moon and Mars. More generally, it examines issues related to the decisions Congress faces in acting on administration funding requests for the SEI. This report derives in part from a workshop on the robotic exploration of the Moon and Mars held at OTA on February 20, 1991. The workshop dealt with issues in robotic and human exploration, the state of A&R research and development (R&D), and the potential for international cooperation. In preparing the report, OTA gathered information from numerous articles and reports. It also conducted personal interviews with a wide variety of individuals familiar with the assessment's issues.

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[1] George Bush, "Remarks by the President at 20th Anniversary of Apollo Moon Landing," The White House Office of Press Secretary, July 20, 1989, p. 3.

[2] Ibid.

[3] George Bush, "Text of Remarks by the President in Texas A&I University Commencement Address," The White House Office of the Press Secretary, May 11, 1990, p. 5.

[4] Specific policy guidance is cited in: Memorandum to National Space Council from Mark Albrecht, "Presidential Decision on the Space Exploration Initiative," Feb. 21, 1990.

[5] Arnold D. Aldrich, NASA Office of Aeronautics, Exploration, and Technology, "The Space Exploration Initiative," presented to the American Association for the Advancement of Science Symposium on the Human Exploration of Space, Feb. 17, 1990, p. 4.

[6] These efforts would extend NASA's planetary exploration program, which has a history of more than 30 years of scientific missions to the solar system.

[7] Aldrich, op. cit., footnote 5, p. 4.

[8] For example, the Space Studies Board of the National Academy of Science and the Synthesis Group, a committee chartered by the White House and NASA to examine alternative ways to establish a lunar base and reach Mars. See *America at the Threshold* (Washington, DC: The White House, June 1991).

[9] Letter to John H. Gibbons from Senator Barbara Mikulski, Congressman Bob Traxler, and Congressman Bill Green, July 24, 1990.

WHAT IS ROBOTICS?

The term "robotics," which generally comprises a significant proportion of automation technologies as well, has within the space program and elsewhere come to connote a wide variety of activities involving humans and machines in partnership. In today's parlance (box 1-A) robotics may be applied to machines entirely under direct human control at short or long distance, but with no automated capability; 2) or it may refer to completely automated devices that carry out preprogrammed tasks on command, but with essentially no capacity to make decisions. Alternatively, 3) the term may apply to machines with a relatively high decisionmaking capacity, capable of operating for extended periods between commands. Finally, 4) robots may continually interact with humans, sometimes acting at a high or low level of autonomy; the human may be nearby or at some distance, even very far away. It is in this last context that future human/robot teams hold particular promise for space activities.

Most applications within NASA have involved robotic devices in category 4, in which the device has always had at least a low capacity for autonomous decisionmaking. Thus, what have previously been termed "unmanned missions" or "planetary spacecraft" are now often called robotic missions. The robotic devices on these missions can be considered *telerobots* because they receive commands over telecommunication links. In addition, NASA has provided their planetary exploration spacecraft a small but growing capacity for *autonomous* action. For example, they are capable of going to a fail-safe mode by automatically recognizing, for example, a loss of navigation lock on guide stars and instituting procedures for recovering to a 3-axis inertially stabilized mode and automatically pointing the communications antenna toward Earth.[10]

Box 1-A—Automation and Robotics for Applications in Space

A central mission of automation and robotics (A&R) technology is to provide a high level of autonomy, or decisionmaking capability, to robotic devices that will enable more effective management of spacecraft, landers, rovers, and other instruments of discovery. Human team members can then guide at any level, and from both small and large distances, because the robot members will have increased capacity for making decisions, as well as increased mobility and manipulative skill. More effective robotics would leave humans free to reason and to control at the most effective level for discovery.

Such *autonomous* robots will largely replace purely "automated" ones that carry out a specified set of preprogrammed functions. Robots with a high degree of autonomy would be capable of responding to new situations with little or no additional guidance from mission control.

From time to time these robots may be *teleoperated* — guided by a human on a continuing basis — at low or high level, and from some distance with possible time lag.

Thus, two of the most important areas of robotics research are to provide humans with greater capability by giving robots: 1) more autonomy, and 2) greater mobility and capacity for manipulation.

SOURCE: Robert Cannon, Stanford University and the Office of Technology Assessment, 1991.

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[10] Because of this capability, in 1990 the *Magellan* spacecraft, which is providing U.S. scientists with a detailed radar map of Venus, was able with the help of mission controllers to recover from a loss of navigation lock. It was the lack of just such an autonomous capability that doomed the 1990 Soviet spacecraft while on its way to Phobos, one of the moons of Mars.

Thus, future efforts in robotics are expected to use advanced techniques, including artificial intelligence,[11] to impart greater capability to humans by giving machines greater autonomy. Robotics research will also involve imparting mobility and a higher capacity for manipulation to robotic devices. In this report, OTA generally uses the term automation and robotics (A&R) to indicate these two major thrusts.

THE HUMAN-ROBOTICS PARTNERSHIP

Both humans and machines can contribute as partners in a Mission from Planet Earth. This partnership raises the following question: what is the appropriate mix of humans and robotic machines on the surface of the Moon and Mars? The answer to this question will shape the program and necessary funding over decades.

At one extreme, the United States could mount Apollo-like expeditions to the Moon and Mars, in which the United States would place maximum emphasis on science and technology to support humans in transit and on the surface, but put relatively little emphasis on A&R. In the Apollo era, because the available A&R technologies were quite primitive, the United States sent men to the Moon with very little robotic support. Most of the control remained on Earth where thousands of support personnel followed every detail of the crew's progress and controlled most of their actions.

At the other extreme, the United States could focus on the development of advanced A&R technologies for exploration and indefinitely defer sending humans to the Moon and Mars.

In the most effective exploration program, people and machines would function as interactive partners, with people on Earth or perhaps on the surface of the Moon or Mars, as need and funding allow. A&R experts believe that it will soon be possible to develop machines, guided by controllers on Earth where appropriate, but acting autonomously most of the time, to carry out many exploration duties. On the Moon, robots controlled from Earth could be used to explore for lunar resources, to conduct scientific observations, and to carry out a variety of simple construction tasks. On Mars, robots could be employed to survey the planet's composition and structure, monitor its weather, and return samples for analysis on Earth.

However, experts in field research methods believe that, even with advances in A&R, human explorers would be needed to carry out geological field studies on the Moon or Mars, or search for signs of indigenous life on Mars — tasks that require a broad experiential database and the ability to link disparate, unexpected observations in the field. Nevertheless, robotic devices would be needed to assist human explorers in a wide variety of tasks as they work on either planetary body.

In the past, A&R technologies have received relatively little emphasis, in part because they have lacked capability. **In the future, giving A&R technologies a more central role in exploration activities could greatly enhance scientific understanding and contribute to increased human productivity in other parts of the economy. Congress can play an important part in assuring that the partnership between humans and machines evolves as productively as possible.** It could, e.g., encourage NASA to:

- devote greater and more consistent effort to A&R research and development; and
- include far more A&R technologies in future projects involving space exploration and humans in space than is the practice today.

EXPLORATION TIMETABLE

Congress also faces a decision regarding the timetable of a Mission from Planet Earth. **Given the existing Federal budget crisis and chronic shortages of public capital, acceptance of the**

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[11] Machine techniques that mimic human intelligence, e.g., perception, cognition, and reasoning.

President's timetable (2019) for landing humans on Mars might require a major emphasis on the development of technologies to support human crews and thus greatly constrain the options for developing A&R technologies.

Some argue that the United States should demonstrate its leadership in advanced technology to the rest of the world by embarking on the human exploration of Mars as soon as possible. However, it is far from clear what the United States would gain from demonstrating leadership in human exploration. For the next decade or even two, the United States has no effective competitors in sending human missions to the Moon or Mars. **If the United States emphasized human exploration and failed to fund the development of A&R technologies directly related to the U.S. economy, it might slip in economic competition with other nations.** A U.S.-led Mission from Planet Earth could assist in boosting international leadership in space activities, but only if it were part of a balanced space program that rested on a solid foundation of space science and technology development.

In the near term, Congress could:

1. *defer decisions on a Mission from Planet Earth indefinitely and fund the scientific exploration of the Moon and Mars within the existing planetary exploration program;* or
2. *agree in principle with the goals of a Mission from Planet Earth, but emphasize the development and use of A&R technologies to accomplish them;* or
3. *agree in principle with the long-term goals of a Mission from Planet Earth, but wish to focus on measured efforts to develop technologies supporting human exploration;* or
4. *accept the President's timetable of people reaching Mars by 2019.*

Options 1 through 3 would tend to extend the timetable for humans to reach Mars beyond 2019.

MANAGEMENT OF A MISSION FROM PLANET EARTH

U.S. experience with large science and technology projects having long-range goals suggest that **program planners need to maintain considerable planning flexibility and a broad set of intermediate objectives within the general program plan. Operational success in each successive phase should be favored over forcing a fit to a detailed long-term plan.**

The scientific success of missions to the Moon and Mars will depend directly on the quality of the scientific advice NASA receives and the relative influence of engineers and designing robotic missions to the Moon and Mars. **If the Nation wishes to maximize the quality of its scientific returns, planetary scientists should have a major role in the decision process about the exploration program**.

EXPLORING AND EXPLOITING THE MOON

Despite U.S. and Soviet successes during the 1960s and early 1970s in studying the Moon, scientists still have a relatively rudimentary understanding of its structure and evolution. A detailed scientific study of the Moon would assist in understanding the geological and climatological history of the Earth. Most of this work could be carried out robotically with a variety of instruments.

The United States may in time wish to establish a permanent lunar base in order to study the Moon more intensively and to exploit its unique properties for scientific observations and experiments. For example, the Moon would provide an excellent site for astronomical observatories operating at all wavelengths. However, the costs of lunar observatories would have to be balanced against the costs of placing observatories in competing locations, e.g., geostationary orbit, or on the Earth.

Exploitation of the Moon's material resources might eventually prove cost-effective, for example, in constructing surface or orbital infrastructure, or in providing additional sources of energy.

Robotic devices would provide human explorers with support for field studies, emergencies, surveys, and construction.

EXPLORING MARS

It is too early to plan a detailed, integrated program of robotics and human exploration of Mars. However, it is not too early to begin a series of projects to continue the scientific investigation of Mars, and to study human physiology in space in order to reduce the uncertainties facing human exploration of the planet.

Robotic exploratory missions will first be needed to explore Mars, whether or not the United States decides to land humans on Mars by 2019. These missions could provide important geological and atmospheric data about Mars, help refine planning for human missions, and assist in choosing potential landing sites.

If the United States ultimately decides that it is important to send human crews to Mars, A&R technologies could provide crucial assistance to these crews while on the Martian surface. A&R could provide support for field studies; assistance in surveying prior to human exploration, especially over dangerous terrain; and emergency support.

A trip to and from Mars would experience much higher risk than a return to the Moon, but would also provide greater challenge and adventure. If the United States decides to send human crews to Mars, it must accept the potential for loss of life, either from human error or mechanical failure.

A&R RESEARCH AND DEVELOPMENT

Robotics exploration will be needed as a prerequisite to human exploration. The United States has many promising A&R technologies, but to date it has not spent sufficient time or funds to incorporate them into devices for exploring the Moon and Mars. **Yet, aggressive pursuit of robotic devices would assist exploration efforts and make humans much more capable on the Moon and Mars than they could otherwise be. However, at present NASA lacks the A&R capability to carry out a vigorous exploration program using advanced robotics. Since the development of robotic technologies does not receive high priority within NASA, there is little evidence to suggest this will change.**

A number of reports, including the recent report of the Advisory Committee on the Future of the U.S. Space Program, have urged increased attention to, and funding for, developing the requisite U.S. technology base. Congress could assist the development of A&R technologies by funding a set of A&R projects that culminated in a variety of scientific capabilities for missions to the Moon and Mars.

The potential applications for A&R technologies extend far beyond the space program and include manufacturing and service industries, as well as the defense community. Yet because the A&R discipline derives from a widely splintered set of subfields, only in weak contact with one another, NASA has a relatively thin technology base upon which to draw for its own needs. **An integrated A&R program to serve government needs and assist industry will require the collaborative efforts of the universities, government laboratories, and industry.**

COSTS

Sending humans back to the Moon and/or on to Mars would be extremely expensive. According to experts OTA consulted,because of the need to support human life in extremely harsh environments, exploration by human crews could cost more than ten times the costs of robotics exploration (see ch. 7). Yet, because cost estimates depend critically on the range of planned activities, schedule, and new information developed in the course of the program, it is too early to judge the total costs of a Mission from Planet Earth. As more information is gained from robotic missions e.g., Mars Observer, and from technology research and development, it will eventually be possible to develop more credible cost estimates.

A comprehensive search for cost-reducing methods and techniques and for alternative approaches will be of high priority. Congress should ask NASA how it plans to control costs. NASA's plans should also include plans for controlling operational costs. As experience with the Space Shuttle has demonstrated, operational costs for crew-carrying systems can constitute an extremely high percentage of total system costs.

A return to the Moon and the exploration of Mars would have a major impact on NASA's yearly budget, and, in times of constrained budgets, pursuit of these goals would almost certainly adversely affect the funding of NASA's other activities, e.g., space science, and the Mission *to* Planet Earth (NASA's program to address environmental and other Earth-bound problems). Hence, it will be important for Congress and the administration to test continually whether the President's aspirations for human activity in space can be accommodated within NASA's likely budget, and adjust its projects accordingly.

INTERNATIONAL COOPERATION AND COMPETITION

Issues of international competition and cooperation will continue to play important roles in the development of U.S. space policy. The United States is part of a rapidly changing world in which the political and military challenge from the Soviet Union has substantially decreased but the technological and marketing capabilities of Europe and Japan have markedly increased. How the United States invests in its space program could deeply affect other segments of the economy. **The experience gained in applying A&R technologies to tasks in space could assist their development in other parts of U.S. industry and help the United States to compete in this important arena of the world economy.** It is less clear how investments to support human exploration of space would benefit U.S. industry.

Politically and technologically, the United States could gain from leading an international cooperative program to advance in space exploration. But for such a space program we will have to learn how to pursue *shared* goals, which would give the United States less latitude in setting the program objectives. Cooperative activities with other countries also could reduce U.S. costs and increase the return on investment for exploration by bringing foreign expertise and capital to bear on the challenge. The Soviet Union has far more experience with supporting humans in space than any other country. More extensive cooperation with the Soviet Union could markedly reduce U.S. expenditures for life sciences research, and lead to much better understanding of the risks of extended spaceflight and how to reduce them.

Japan, Europe, and the Soviet Union have made significant progress in applying A&R to space activities. Cooperative scientific programs that would incorporate robotic devices contributed by several countries might significantly advance U.S. experience in this important area. For example, nations might cooperate in sending small rovers to the Moon or to Mars to do reconnaissance and simple chemical analysis, and to return samples to Earth.

Chapter 2
Policy and Findings

President Bush has set forth two major goals for the U.S. space program — developing a permanent human presence on the Moon, and landing a human crew on Mars — under the broad principle of extending "human presence and activity beyond Earth orbit into the solar system."[1] These are two of many goals for civilian space activities the U.S. Government could pursue.[2] The Advisory Committee on the Future of the U.S. Space Program[3] has recommended that "the 'mission-oriented' portion of the program [NASA's] be designed to support two major undertakings: a Mission *to* Planet Earth and a Mission *from* Planet Earth."[4] As seen by the Committee, the Mission *to* Planet Earth emphasizes using robotic space technology to tackle environmental and other Earth-bound problems. The Mission *from* Planet Earth would focus on the exploration of space, using human crews as well as robotic systems. In the Committee's view, both mission foci should rest on the foundation of space science and an enabling technology infrastructure.[5]

During this decade, Congress will be faced with a series of decisions concerning whether or not to invest public dollars to send human crews back to the Moon and/or on to Mars,[6] decisions that cannot be reduced to scientific and technological considerations alone. Experience suggests that management, politics, and budgets — as they interact with technical factors — will shape the success or failure of *any* initiative to explore space, whether solely with robotic devices, or using both robots and humans. **Mission from Planet Earth will be very complex, requiring new technologies and taking many years. It will therefore be shaped by a continuous decision process extending over numerous budget cycles. The funding and political support for an initiative to explore the Moon and Mars must be provided over many Presidencies and Congresses.** Therefore, projects should be defined with an eye to returning nearterm benefits. Because the cast of participants will change over time (in 2-, 4-, and 6-year intervals), funding commitments to Mission from Planet Earth will have to be renewed on the basis of performance by NASA and the other agencies, and the standards of performance will change as new information is gained.

Both humans and robotic spacecraft will contribute to solar system exploration whether or not humans set foot on the Moon or Mars within the next three decades. The Congress must decide the appropriate mix of humans and robotic technologies to fund within the set of projects that make up a Mission from Planet Earth.[7] The *timing* of its decisions will depend upon Congress' view of the President's proposed timetable of enabling human crews to reach the surface of Mars by 2019. **Given the imperative to reduce Federal spending, acceptance of the President's timetable might greatly circumscribe the options for using automation and robotic (A&R) technologies to**

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[1] The White House, "National Space Policy," Nov. 2, 1989, p. 1.

[2] See, e.g., the list in U.S. Congress, Office of Technology Assessment, *Civilian Space Stations and the U.S. Future in Space*, OTA-STI-242 (Washington, DC: U.S. Government Printing Office, November 1984), pp. 15-16.

[3] Advisory Committee on the Future of the U.S. Space Program, *Report of the Advisory Committee on the Future of the U.S. Space Program* (Washington, DC: U.S. Government Printing Office, December 1990). The National Space Council and NASA appointed the Advisory Committee to examine the goals and managment of the U.S. space program. Norman Augustine, CEO of Martin Marietta Corp., served as its chair.

[4] Ibid, p. 5.

[5] Ibid, p. vi and 5.

[6] Although the Moon's surface would provide human crews with experience in living and working in space, the Nation could decide to proceed directly to Mars.

[7] This report entered the publishing process before the Synthesis Group report on alternative technologies and exploration architectures was released. Hence, it was unable to consider the Synthesis Group's findings.

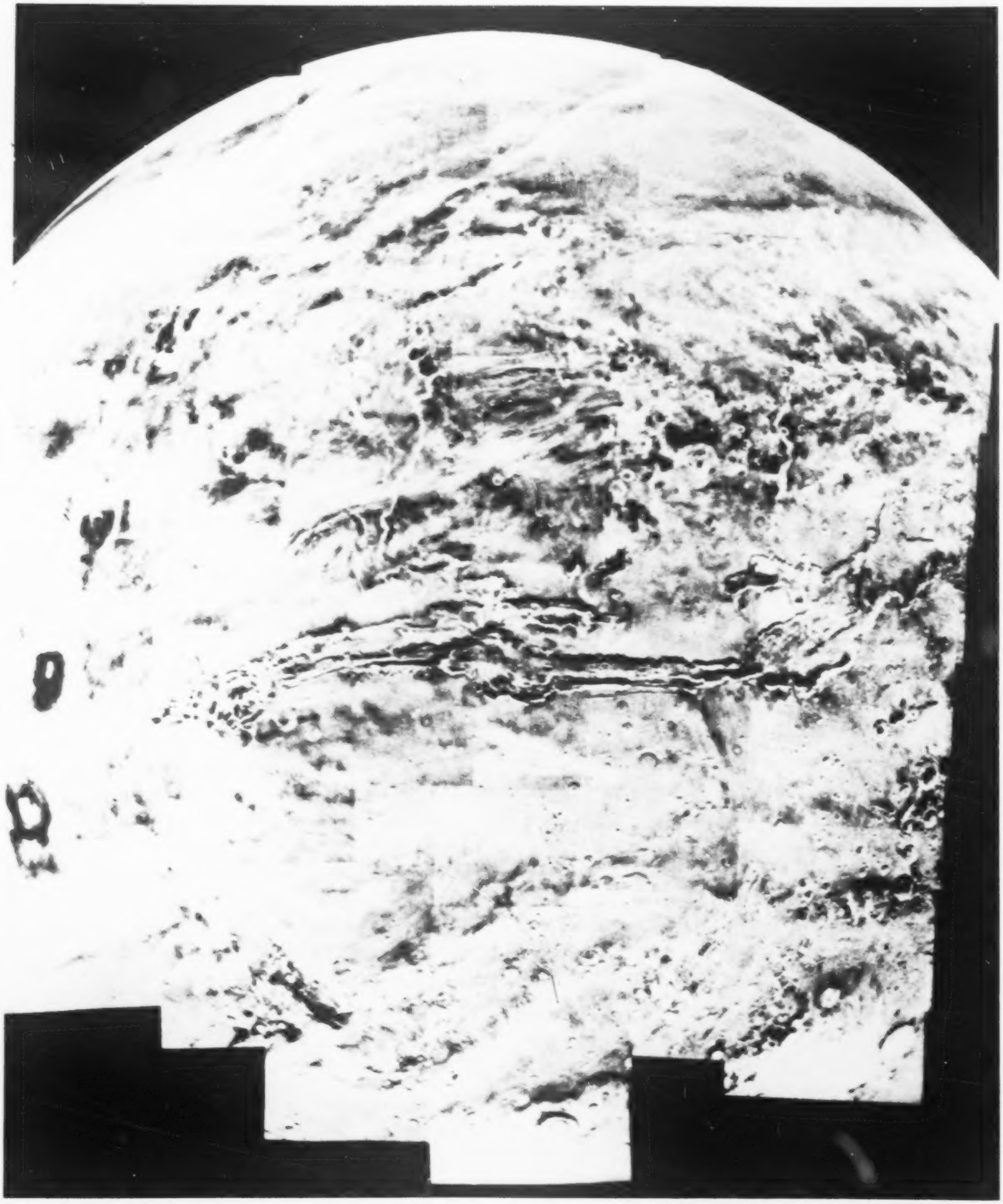

Photo credit: National Aeronautics and Space Administration

Mosaic of 102 images of Mars taken by NASA's Viking Orbiter 1, Feb. 22, 1980. Valles Marineris, which is as long as the distance from New York to San Francisco, stretches across the center. Three huge volcanoes of the Tharsis region appear on the left.

support planetary exploration, and require a major emphasis on technologies and systems to support human crews. Taking a broader view of the many possible paths for the Mission from Planet Earth permits consideration of a wider range of technological options and timetables. For example, Congress could:

1. *Defer decisions on a Mission from Planet Earth indefinitely and fund the scientific exploration of the Moon and Mars within the existing planetary exploration program.*

   If Congress chose to defer decisions on human exploration of the Moon and Mars, it could continue to fund the scientific exploration of these two celestial bodies within the existing planetary exploration program. This approach would place the exploration of the Moon and Mars within the context of other space science priorities. However, unless Congress appropriated a higher proportion of funding for space science than the customary 20 percent of NASA's total budget,[8] or sharply reduced funding for other space science missions, this choice would allow only modest exploration efforts.

2. *Agree in principle with the goals of a Mission from Planet Earth, but emphasize the development and use of A&R technologies to accomplish them.*

   Alternatively, if Congress supported the long-term goal of human exploration of the solar system, and felt that robotic technologies should receive greater emphasis, it could endorse the President's goals in principle but defer funding of systems to support human exploration until better information on risks and costs becomes available. It could in the meantime direct NASA to enhance its efforts in robotic exploration of the Moon and Mars. As scientists learn more about these celestial bodies, and develop more capable robotics technologies, Congress could then decide whether or not to fund the development of technologies necessary for supporting human exploration. This option would have the effect of emphasizing the scientific exploration of the Moon and Mars compared to the rest of the space science effort. It would also extend the President's proposed timetable for humans to set foot on Mars by several years and allow NASA to gather additional scientific information to support a later congressional funding decision on human exploration. This option would require additional funding for exploration over current allocations.

3. *Agree in principle with the long-term goals of a Mission from Planet Earth, but wish to focus on measured efforts to develop technologies supporting human exploration.*

   If Congress agreed with the long-term goal of human exploration of the solar system, but felt that the United States should proceed cautiously with human exploration, as well as learn much more about the conditions on Mars, the risks to human life, and the predicted total costs of a Mission from Planet Earth, it could endorse the President's goals and fund selected technologies required for human exploration, while also funding the development of robotic technologies to aid human explorers. For example, Congress could ask NASA and the Department of Defense (DoD) to proceed with the development of propulsion and other space transportation technologies for a new launch system, but defer development of in-space nuclear propulsion, or technologies to provide artificial gravity in flight until more is known about the space environmental risks humans face. In order to assist its later decisions on funding a permanent lunar base, or human exploration of Mars, Congress could ask NASA to study key scientific and technological issues and report back to Congress at predetermined intervals.

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[8] The space science and applications budget has equaled about 20 percent of NASA's total budget since the mid-1970s. Ronald M. Konkel, "Space Science in the Budget: An Analysis of Budgets and Resource Allocation the NASA, FY 19611989," Center for Space and Geosciences Policy, University of Colorado, Boulder, CO, May 1990.

4. *Accept the President's timetable of reaching Mars by 2019.*

Finally, Congress could accept the President's timetable of reaching Mars by 2019 and decide to fund projects designed to achieve that goal. This option would require NASA, DoD, and the Department of Energy (DOE) to begin a range of studies detailing the technical options for meeting the President's goal. It would also require the near-term development of a heavy-lift launch system, life-support systems, and other technologies necessary to transport humans to the Moon and Mars and support them on the surface. Finally, this option would also require development of A&R technologies to gather early scientific knowledge of Mars and to improve human productivity on both the Moon and Mars.

In its report, the Advisory Committee on the Future of the U.S. Space Program shares "the view of the President that the long term magnet for the manned space program is the planet Mars." However, it suggested that "a program with the ultimate, *long-term* objective of human exploration of Mars should be tailored to respond to the availability of funding, rather than to adhering to a rigid schedule."[9] Options 2 and 3 fit within the Committee's recommendations, but emphasize somewhat different approaches to technologies and schedule.

PLANETARY EXPLORATION POLICY AND NATIONAL GOALS

In recent debate, the space program's close connection to broad national concerns has manifested itself in the propositions that human exploration of the Moon and Mars would help reestablish U.S. leadership in space,[10] further the development of U.S. science and technology,[11] and assist its economic competitiveness abroad.[12] In 1986, the National Commission on Space advanced the additional view that the solar system is "humanity's extended home" and that the United States should use its economic strength to lead the rest of the world in exploring, and eventually settling, the Moon and Mars.[13] According to this view, the technological challenge of returning to the Moon and sending humans to explore Mars would create strong public interest, nationally and internationally, and enhance attention to science and technology.[14]

These varied perspectives — destiny, world leadership, economic expansion — raise several overarching issues for Congress to consider in authorizing and funding the U.S. civilian space program of the 1990s. The roles of A&R in space exploration are embedded in each of them:

- In the 1960s, the Kennedy and Johnson administrations and Congress explicitly designed the Apollo program to establish U.S. preeminence in science and technology. Would demonstrating preeminence in the next century through planetary exploration by robots or human crews serve U.S. political and economic goals?
- Over the years, the United States has used the civilian space program to support both

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[9] Advisory Committee on the Future of the U.S. Space Program, op. cit., footnote 3, p. 6.

[10] Sally K. Ride, *Leadership and America's Future in Space* (Washington, DC: National Aeronautics and Space Administration, August 1987).

[11] Arnold D. Aldrich, "Myth and Reality: NASA and the Space Exploration Initiative," paper presented at the Space Exploration 90 conference, Oct. 30, 1990.

[12] Charles Walker, "Remarks to the Scientists' Hearing on Human Mission to Mars," *Journal of the Federation of American Scientists (FAS)*, vol. 44, No. 1, January/Febuary 1991, p. 14.

[13] National Commission on Space, *Pioneering the Space Frontier: The Report of the National Commission on Space* (New York, NY: Ballentine, 1986), pp. 3-4.

[14] Synthesis Group, *America at the Threshold* (Washington, DC: The White House, June 1991), pp. 104-111.

competitive and cooperative ends. Should it view space exploration primarily as a vehicle for international competition or as an instrument for cooperation? Or can it effectively pursue both objectives?

- Would public investments in space A&R, or in technologies for supporting humans in space, contribute to overall science and technology goals, including education?

Another issue emerges from consideration of the organization and management of the Mission from Planet Earth:

- The United States has funded the civilian space program in part to enhance America's skills in science and technology. The Mission from Planet Earth would employ both people and machines in locations ranging from the surface of Earth to the surfaces of the Moon and Mars. What is the proper mix of capabilities, locations, and timing, given U.S. economic, political, scientific, and technological goals and constraints? These judgments must be made within the context of competing national priorities and should include estimates of the costs and risks.

A detailed examination and resolution of these issues is beyond the scope of this report. The following discussion outlines the considerations that policymakers face in reaching decisions on them.

From its inception, the U.S. civilian space program has been an instrument of U.S. domestic and foreign policy;[15] its structure and early direction resulted directly from the tensions of the cold war.[16] Because most spending on space activities still flows from the public purse,[17] overall domestic and foreign policy will continue to dominate decisions regarding these activities.[18]

In 1961 when President Kennedy urged Congress to support the Apollo program the United States was in midst of the cold war. Policymakers then felt that it was particularly important to demonstrate U.S. technological competence in an arena in which our chief political and military competitor had taken the lead. The United States and the Soviet Union were clearly in a space race.[19] The U.S. economy was strong and growing, and the Federal Government experienced modest budget surpluses.

Today, the political, military, and economic character of the world is radically different than it was even on July 20, 1989, when President Bush outlined his plan for human exploration of the solar system. Relations between the Soviet Union and the United States have moved from implacable opposition to guarded cooperation. The Soviet Union is experiencing considerable internal political and economic stress, the Warsaw Pact has dissolved, and central Eastern Europe is undergoing radical and trying political and economic change. U.S. and NATO policies are increasingly tending toward cooperation with the Soviet Union, to help it move toward democracy and a modern economy, and deemphasizing political competition.[20] During the recent crisis in the Persian Gulf, e.g., the United States sought cooperation with the Soviet Union, as well as with our traditional allies.

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[15] Walter McDougall, *The Heavens and the Earth* (New York, NY: Basic Books, Inc., 1985).

[16] Vernon Van Dyke, *Pride and Power: The Rationale of the Space Program* (Urbana, IL: University of Illinois Press, 1964); John M. Logsdon, *The Decision To Go to the Moon* (Boston, MA: MIT Press, 1970).

[17] A small portion of total civilian expenditures on space derive from private investment. Most of these depend on Government contracts: Henry Hertzfeld, "Trends in International Space Activity." In *The U.S. Aerospace Industry in the 1990's: A Global Perspective*, Research Center, Aerospace Industries Association of America, forthcoming, September 1991.

[18] The Bush Administration's 1989 statement of space policy refers explicitly to broader objectives in stating that the objectives of the space program "require United States preeminence in the key areas of space activity critical to achieving our national security, scientific, technical, economic, and foreign policy goals."

[19] The February 1991 NOVA special documentary series on the Soviet space program reveals that Soviet officials also saw themselves in a race with the United States for supremacy in space.

[20] Manfred Worner, "The Atlantic Alliance in the New Era," *NATO Review*, vol. 39, No. 1, pp. 3-10.

Unlike 30 years ago, our allies are now our strong economic competitors, particularly in defense and other high technology industries.[21] **How the U.S. Government chooses to invest in R&D will have profound implications for economic competition. Although demonstrating U.S. technological prowess with a major space initiative involving human spaceflight would probably strengthen U.S. leadership in space, it is not clear what message that feat would send to the rest of the world.** Neither the Europeans nor the Japanese have placed the same emphasis on putting humans into space as have the United States and the Soviet Union. The European Space Agency has expressed an interest in exploring Mars robotically,[22] and the Japanese have announced plans to send robotic craft to the Moon.[23] The Soviet Union has reduced its funding for supporting a human presence in space,[24] and, given its current fiscal and political problems, it appears to lack the financial and technological resources to mount a human mission to Mars on its own. Hence, **for the next decade or two, the United States has no effective competitors in sending human missions to the Moon or Mars. Therefore, although a U.S. initiative to send human explorers to the Moon or Mars would be an accomplishment, it would not be a race with other nations. Would the United States be better or worse off than nations that spent R&D funds to realize more prosaic goals?**

Although Japan and the countries of Europe combined spend much less on space activities than the United States (table 2-1), Japanese and European technological capabilities in space and in larger areas of the economy have grown substantially over the last two decades. Europe's relative emphasis on space science, space applications,[25] and space transportation has enabled it to pose a formidable competitive challenge to U.S. space industries.[26] Both the Japanese and the Europeans have generally sought autonomy in these areas, using cooperative ventures with the United States to help achieve it. Japan and the European countries tend to enter into technology development that they perceive relates directly to their economies over the near and long term. The space A&R programs of Canada, Japan, and Europe, e.g., are relatively well integrated in content; represent a common thrust within industry, academia, and government; and focus on goals of interest to the nation's economy and competitive-

Table 2-1 — Spending on Civilian Space Activities by the World's Major Industrialized Nations

Country	Space budget (fiscal year)
Canada	$285 million (4/90-3/91)
European Space Agency (ESA)	$2.2 billion (1/90-12/90)
France	$1.7 billion (1/90-12/90) [$601 million to ESA]
Germany	$911 million (1/90-12/90) [$507 million to ESA]
Italy	$976 million (1/90-12/90) [$375 million to ESA]
Japan	$1.2 billion (4/90-3/91)
United Kingdom	$296 million (4/89-3/90) [$134.6 million to ESA]
Soviet Union	$4.8 billion (FY 1990)[a]
United States	$12.5 billion (FY 1990)

[a] This official estimate is likely to be much lower than actual expenditures, when compared to U.S. dollars.

SOURCE: George D. Ojalehto and Richard R. Vondrak, "A Look at the Growing Civil Space Club," *Aeronautics and Astronautics*, February 1991, pp. 12-16.

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[21] U.S. Congress, Office of Technology Assessment, *Arming Our Allies: Cooperation and Competition in Defense Technology*, OTA-ISC-449 (Washington, DC: U.S. Government Printing Office, May 1990).

[22] European Space Agency, *Mission to Mars: Report of the Mars Exploration Study Team* (Paris, France: European Space Agency, January 1990).

[23] T. Iwata, "NASA's Unmanned LUNAR Exploration," IAF 90-438, presented at the International Astronautical Federation Annual Meeting, Dresden, Germany, October 1990.

[24] Nicholas L. Johnson, *The Soviet Year in Space 1990* (Colorado Springs, CO: Teledyne Brown Engineering, February 1991), pp. 98-122.

[25] That is, communications, meteorological observations, and land and ocean remote sensing.

[26] U.S. Congress, Office of Technology Assessment, *International Cooperation and Competition in U.S. Civilian Space Activities*, OTA-ISC-239 (Washington, DC: U.S. Government Printing Office, July 1985).

ness.[27] **Because of their relative emphasis on achieving autonomy, especially in commercially viable areas of the space enterprise, and their interest in using the space program to foster long-term economic growth, neither Japan nor the countries of Europe are likely to attempt competing with the United States in activities involving human crews in space for a decade or more.[28]**

As a recent study by the Congressional Budget Office has noted, NASA's attempts to increase private investment in space activities based on NASA's efforts to support humans in space have produced limited results[29] in part because, compared to satellite communications or space remote sensing,[30] the technologies involved have relatively few direct applications to U.S. industry. Hence, although a large publicly supported program to establish a lunar base or send humans to Mars would probably create new jobs in the aerospace industry, unless carefully structured, it might not contribute significantly to U.S. economic competitiveness. If it diverted scarce resources (funding and people) away from projects having a closer connection to the U.S. economy, a major initiative involving human crews might actually undercut the U.S. international position in commercially competitive technologies.

If the experience of the Apollo program provides an appropriate guide to the future, sending human crews to explore Mars would likely create public interest in the space program and encourage some young people to enter careers in engineering, mathematics, or science. It might provide jobs for scientists and engineers faced with layoffs in the declining defense industry. However, the experience with Apollo also demonstrated that the public's primary interest was with the novelty and challenge of human spaceflight and a desire to beat the Soviet Union to the Moon. Soon after the first Apollo landing, interest waned as concern about social equity and the Vietnam War increased. Funding for the space program peaked in 1965 and reached a low point in 1974. Although some percentage of the public maintains deep interest in human spaceflight, the government cannot take for granted continuing public support for large expenditures on the space program in competition with other pressing societal needs, in the absence of clear evidence that they would directly benefit society.[31]

THE "MIX" OF HUMAN CREWS AND ROBOTICS FOR EXPLORATION

Exploration of the solar system will require a complex mix of humans and robotic systems — as some have put it, "a partnership between humans and machines."[32] The *placement* of robotic devices and humans at different stages of the exploration process would depend on available funding and the relative advantages of humans and machines for the projected task at hand. For example, current plans call for the use of robots on Mars to carry out initial reconnaissance of the Martian surface. Among other things, robots would explore and define the local environment and clarify the risk for humans. The human role in the partnership would be to oversee the robot's operation on the surface. Later, humans might visit the surface of Mars to explore it firsthand, using A&R technologies to support their efforts.

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[27] NASA Advanced Technology Advisory Committee, "Advancing Automation and Robotics Technolgy for the Space Station *Freedom* and for the U.S. Economy," Technical Memorandum 103851 (Washington, DC: Ames Research Center, National Aeronautics and Space Administration, May 1991).

[28] For budgetary reasons, Europe is now reassessing its spending for the Columbus Program to build a crew-tended free flyer, and has slowed its development of the Hermes piloted space plane.

[29] Congressional Budget Office, *Encouraging Private Investment in Space Activities* (Washington, DC: U.S. Government Printing Office, February 1991).

[30] The attempts to commercialize space remote sensing in the United States have met with considerable frustration. Yet a small, and growing commercial market exists, particularly in providing value-added services. See U.S. Congress, Office of Technology Assessment, *Remote Sensing and the Private Sector*, OTA-TM-ISC-20 (Washington, DC: U.S. Government Printing Office, 1984).

[31] "Twenty years after America first put men on the moon, the public shows only a limited commitment to the U.S. space program. This lukewarm attitude about future space exploration is a consequence of increased awareness of domestic problems, coupled with decreased concern for the U.S.-Soviet rivalry that propelled the space race during the 1960s." George Gallup, Jr., *The Gallup Public Opinion 1989, 1990*, p. 172.

[32] Louis J. Lanzerotti and Marc S. Allen, "Space Science Payoffs in an Era of Human-Machine Partnership, paper presented at the American Association for the Advancement of Science, Annual Meeting, Washington, DC, February 1991.

Nearly all the advocates of space exploration that OTA interviewed for this assessment expressed the view that humans would one day return to the Moon and set foot on the surface of Mars. They differed widely in their predictions about why and when those events would take place. Opinions regarding the most appropriate schedule differed even more widely. Some ardently support the establishment of a lunar outpost and/or the human exploration of Mars as soon as possible (by 2019 or sooner); others expressed the view that the United States should approach such projects with caution and suggested that a later date for a Mars landing would be more prudent. All supported continued robotic exploration.[33] Several opined that from a scientific standpoint, advances in A&R technologies might make the goal of landing humans on the surface of Mars superfluous, but noted that other objectives could still draw the United States to support a human expedition to the planet.

Most scientific objectives for the exploration of the Moon and Mars can be met with A&R technologies. On the Moon, robots controlled from Earth can be used to explore for lunar resources, to conduct scientific observations, and to carry out a variety of construction tasks. However, experts in field research methods believe that even with advances in automation and research, human explorers are likely to be most effective in carrying out geological field studies on the Moon and Mars, or searching for signs of indigenous existing or fossil life on Mars. These tasks involve complex skills, including recognition of subtle clues, and detailed assessment and analysis.

Both humans and machines would be involved in any program aimed at returning to the Moon or exploring Mars. For a given set of scientific objectives, the appropriate mix of duties and locations is a technical decision that should be determined by the relative advantages of each. A&R technologies provide powerful tools for studying the planets either at a distance or on the surface. Except for human reconnaissance on the lunar surface in the Apollo program, all other scientific studies of the planets and their associated moons and other satellites have been carried out with marked success using automated and robotic systems.[34] A&R experts forecast that continuing developments in using artificial intelligence and advanced control and manipulation would give A&R systems the capability to carry out advanced surface studies of the Moon and Mars, guided by humans either in situ, in nearby orbit, or on Earth. Advanced sensors, similar in many respects to those being developed for the Mission to Planet Earth, would make detailed multispectral observations from orbit much more effective than previously possible.[35]

Field geologists[36] and biologists[37] contend that imparting their skills, knowledge, and experience of fieldwork to robotic systems, acting alone, may never be possible. Although A&R experts forecast significant improvements in A&R over the next three decades, A&R devices are likely to fall short in areas in which humans excel — those that require a broad experiential database and the

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[33] See also Advisory Committee on the Future of the U.S. Space Program, op. cit. footnote 3, p. 6: "such an endeavor must be preceded by further unmanned visits..."

[34] Space exploration, whether by humans or robotic devices, also carries a high degree of technical risk. As the Soviet experience with their *Phobos* spacecraft reminds us, robotic devices sometimes fail, causing loss of mission or reduced effectiveness.

[35] Recent observations of the Moon by the imaging system on the Galileo Jupiter space probe illustrates how such observations can advance scientific knowledge of the planets.

[36] Paul D. Spudis and G. Jeffery Taylor, "The Roles of Humans and Robots as Field Geologists on the Moon," in *Proceedings of the 2nd Lunar Base Symposium* (San Diego, CA: Univelt, 1990).

[37] Christopher P. McKay and Carol R. Stoker, "The Early Environment and Its Evolution on Mars: Implications for Life," *Reviews of Geophysics*, vol. 27, No. 2, 1989, pp. 189-214.

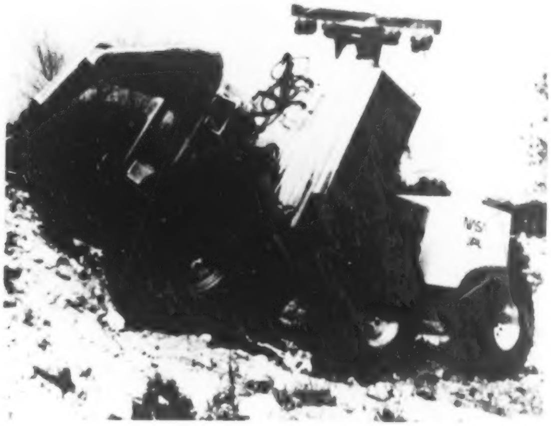

Photo credit: National Aeronautics and Space Administration

An experimental planetary rover undergoing tests in a dry river bed. Nicknamed "Robby," this rover was developed by Jet Propulsion Laboratory, under contract to NASA. Robby is a six-wheel, three-body articulated vehicle that offers superior mobility compared to four-wheel, single-body vehicles. Robby has an arm to grasp soil and rock samples. Stereo cameras mounted atop the middle body allow Robby to construct a map of its local environment and navigate autonomously around obstacles to reach a predetermined goal.

ability to link disparate, unexpected observations in the field. Reconnaissance on the Moon by Apollo astronauts, e.g., provided the basis for interpreting data acquired remotely. Field scientists point out that as A&R technologies grow more sophisticated, their ability to assist fieldwork will make human explorers, whether located on-site or at great distances, much more capable than they are today. Hence, according to their view, humans, using advanced A&R technologies for support and field analysis, are likely to advance our scientific knowledge of the Moon and Mars significantly. By observing geological formations in the field, trained field geologists could provide important data on the formation and evolution of the Moon and Mars. Biologists and geologists trained in the specialized methods of exobiology would be able to search for signs of past or present life on the Martian surface.[38]

However, scientists would need to remain on the Martian surface long enough to accomplish worthwhile research and other tasks. They would also have to be relatively safe and reasonably comfortable. Soviet experience on *Mir* suggests that human productivity in space might be relatively low.[39] U.S. experience on the Apollo flights and on Skylab indicates the potential for higher productivity, especially if assisted by modern A&R technologies, designed to reduce the burden of routine tasks.

MANAGEMENT OF EXPLORATION

U.S. experience with large science and technology projects and long-range goals suggest that program planners need to maintain considerable planning flexibility and a broad set of intermediate goals within the general direction. Operational success in each successive phase should be favored over forcing a fit to a long-term plan.

Lessons based on experience with the space shuttle[40] and with space station *Freedom*[41] imply that "success-oriented" planning, which leaves little room for the vagaries of the political process or technical setbacks, may lead to much higher than expected costs, and long delays in accomplishing major technical goals. A successful strategy for exploring the Moon and utilizing its resources and exploring Mars would include allowance for the unexpected. These lessons suggest that these goals could be met most effectively by developing an integrated strategy that includes both large and small projects, each of which contributes to the larger goal. They also suggest that a successful evolutionary strategy would include the following characteristics:

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[38] Experience with using robotic devices to explore Lake Hoare, Antarctica, demonstrates that they provide extremely important support services. That experience suggests that planetary scientists might wish to make extensive use of A&R techniques to extend human perception into a hostile environment before attempting human presence. Learning as much as possible about the hostile environment enables the safest and most efficient use of human resources in conducting scientific research. Steven Squyres, Cornell University, personal communication, 1991.

[39] Cosmonaut Gregory Grechko, personal communication, March 1991.

[40] John M. Logsdon, "The Space Shuttle Program: A Policy Failure?" *Science*, vol. 232, May 30, 1986, pp. 1099-1105.

[41] Ronald D. Brunner and Radford Byerly, Jr., "The Space Station Programme," *Space Policy*, vol. 6, No. 2, May 1990, pp. 131-145; Thomas J. Lwein and V.K. Narayanan, *Keeping the Dream Alive: Managing the Space Station Program, 1982-1986*, NASA Contractor Report 4272, National Aeronautics and Space Administration, July 1990; Howard E. McCurdy, *The Space Station Decision: Incremental Politics and Technical Choice* (Baltimore, MD: Johns Hopkins University Press, 1990).

- *Flexibility* — Planners should not attempt to "freeze" or "lock-in" a large-scale, long-term plan tightly coupled to expected funding. A balanced, flexible plan would allow investigators to learn from experience, and give them room for changes in scope and project direction depending on information received and funding available. However, because a very flexible plan could also lead to stretchouts, reorganizations, and loss of project momentum, the areas of project flexibility need to be carefully structured.

- *A set of intermediate, phased goals structured around a common theme* — Planners should resist the tendency to design a large-scale project in order to include every objective under the aegis of a large program. Instead they should disaggregate the often incompatible goals of multiple constituencies, approaching the goals through multiple projects, executed either in parallel or in series. These steps would allow planners to learn from the successes or failures of early projects and factor these lessons into subsequent projects.

- *A management structure that favors operational experience over planning* — Experience and a judgment about what works best should be the primary test of the succeeding stages in the exploratory process, rather than a plan developed prior to the results of the first stage.

- *Streamlined management and procurement* — Wherever possible, contract for specified capabilities rather than specified hardware. In other words, allow industry to determine the technologies and approaches to providing the required capabilities rather than having government laboratories decide.

The scientific success of exploratory missions to the Moon and Mars will depend closely on the quality of the scientific advice NASA receives, funding stability for a long-term program, and the relative influence of scientists in designing the missions. If the Nation wishes to maximize the quality of its scientific returns,[42] scientists should have a major role in the process of deciding how exploration resources are spent. The Space Science Board of the National Academy of Sciences and other advisory groups could play a useful part in the decision process.

A number of scientists interviewed by OTA expressed serious concern that scientific objectives would soon be lost in the drive to gather only the data necessary to support a human exploratory mission to Mars. Several cited the case of the *Ranger* and *Surveyor* series of lunar probes, which prior to the Apollo program had been planned for studying the Moon. The *Ranger* probes were designed to photograph the lunar surface in detail. *Surveyor* spacecraft were to make soft landings and gather information about the chemical and physical makeup of lunar soil. The advent of the Apollo program in 1961, "forced *Ranger* and *Surveyor* into supporting roles for the manned spaceflight program, to the intense chagrin of the space scientists."[43] Reorientation of the roles of these spacecraft forced the scientists, if they wished to continue working on lunar science, to pursue scientific questions that were possible within the constraints of the Apollo program rather than pursuing questions of highest scientific interest.[44] The two objectives may coincide, but only accidentally. Hence, the non-scientific objectives of the Mission from Planet Earth should not dominate the scientific objectives.

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[42] The Advisory Committee on the Future of the U.S. Space Program noted that science activity is "the fulcrum of the entire civil space effort." Advisory Committee on the Future of the U.S. Space Program, op. cit., footnote 3, p. 5.

[43] William David Compton, *Where No Man Has Gone Before* (Washington, DC: U.S. Government Printing Office, 1989), p. 15.

[44] Ibid., chs. 2 and 3.

RETURNING TO THE MOON

Despite U.S. and Soviet efforts during the 1960s and early 1970s to study the Moon, scientists still have a rudimentary understanding of its structure and evolution. A detailed robotic study of the Moon would assist in understanding the geological and climatological history of the Earth.

Only about 40 percent of the lunar surface has been mapped in high resolution. Scientists have studied very little of the surface with multispectral instruments, which would provide detailed insights into the structure and composition of the Moon. Scientific exploration of the Moon could assist in resolving questions related to:[45]

- *Formation of the Earth-Moon system* — Did the Moon form from the impact of a giant body with Earth or directly from accretion out of the primordial material?
- *Thermal and magmatic evolution of the Moon* — What is the Moon's internal structure and thermal evolution?
- *Bombardment history of the Earth-Moon system* — What can the composition and other properties of the lunar craters tell us about the bombardment history of Earth, the evolution of Earth's climate, and the evolution of life?
- *Nature of impact processes* — How do craters form and evolve?
- *Regolith formation and evolution of the Sun* — What can studies of the regolith, the blanket of broken rock and soil that covers the Moon, tell us about the evolution of the Sun? How can regolith be used for building lunar structures?
- *Nature of the lunar atmosphere* — What is the nature of the extremely tenuous lunar atmosphere?

Detailed answers to these questions would require intensive lunar survey and additional samples from the Moon.

The Moon possesses several advantages as a site for astronomical observatories operating at all wavelengths. However, the costs of lunar observatories would have to be balanced against the costs of placing observatories in competing locations, e.g., geostationary orbit. The environmental advantages of making astronomical observations from the Moon have interested many astronomers in analyzing the scientific benefits of such sites.[46] The Moon provides a nearly atmosphere-free environment; a large, solid platform; a cold, dark sky; and the absence of wind. Specialized telescopes operating in a wide variety of wavelengths could possibly be placed on the lunar surface robotically and operated from Earth.[47] If the United States decides to establish a permanent lunar base, human crews could construct and maintain larger observatories. The lunar far side offers attractive sites for making sensitive radio observations free from radio interference emanating from Earth stations.

The lunar surface also poses several environmental challenges—among which are the constant bombardment of cosmic rays and micrometeoroids, and the effects of clinging lunar dust. The costs of building and operating lunar observatories have not been well studied in comparison to other possible sites, e.g., geostationary orbit or on Earth.[48] As astronomers continue to examine the option of placing observatories on the Moon, they should also calculate the costs (for equivalent capability) relative to other options.

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[45] Lunar Exploration Science Working Group, *A Planetary Science Strategy for the Moon*, draft, Sept. 28, 1990.

[46] The Astronomy and Astrophysics Survey Committee of the National Research Council recently recommended that "an appropriate fraction of the funding for a lunar initiative be devoted to fundamental scientific projects, which can have a wide appeal to the U.S. public; to support of scientific missions as they progress from small ground-based instruments, to modest orbital experiments; and finally, to the placement of facilities on the Moon." *The Decade of Discovery in Astronomy and Astrophysics* (Washington, DC: National Academy Press, 1991), p. 7.

[47] Russell M. Genet, "Small Robotic Telescopes on the Moon," a workshop summary, Tucson, AZ, Nov. 4-5, 1990.

[48] New technologies may vastly extend the observational capabilities of Earth-based observatories for optical wavelengths.

A lunar base could assist human crews in studying and responding to the risks of long-term space exploration. Human crews engaged in long-term exposure to the space environment face a variety of physiological and psychological risks to their health. In order to provide adequate margins of safety for human crews, scientists must learn how to avoid cosmic rays and excessive radiation from solar flares and to offset the physiological effects of weightlessness, and extraterrestrial fractional gravity.[49] Human crews also face psychological risks from extended confinement in small quarters in an extremely hostile exterior environment. Extended stays on the lunar surface could provide scientists and crews with useful information on many of these effects, leading to reduced risks for human crews in the exploration of Mars.[50]

Exploration of the Moon using a robotic roving vehicle and other robotic devices would provide additional scientific and engineering data and give mission planners extra confidence in designing similar devices for use on Mars. They might find it fruitful to establish a robotics lunar base. Although lunar gravity is one-half that of Mars, and the lunar surface has different properties, testing robotic devices on the Moon would not only provide scientists with data of considerable scientific interest but also help reduce the risk of failure for similar devices on the surface of Mars.

Because the Moon is much closer than Mars it is possible to operate robotic devices in near real time. Communications time delays are only about 3 seconds compared to delays of 6 to 40 *minutes* between Earth and Mars. Tests would also allow engineers to try out alternative methods for including varying degrees of autonomy in robotic systems while exploring the Moon.[51] Because transportation and other costs are much lower than for reaching Mars, the lunar surface would provide tests of competing robotic designs. For example, recent cost estimates suggest that small rovers could be tested on the lunar surface relatively cheaply and also provide useful scientific knowledge about the Moon.[52]

Minerals and other materials extracted from the lunar surface could provide most of the material needed for a lunar base. They could also be used for building infrastructure near the Moon. If the United States were to establish a permanently inhabited lunar base, it could construct the base from the regolith. Future activities might include mining minerals for use on the Moon or in near-lunar space, or using the Moon as an energy source.[53]

EXPLORING MARS

Scientists do not sufficiently understand the Mars environment and the risks to human life to ensure relatively safe human exploration of the planet. Hence, it is too early to plan a detailed, integrated, long-term program that presupposes human exploration of Mars. However, it is not too early to begin planning a sequence of projects that would: 1) make a detailed scientific investigation of Mars, and 2) study human physiology in space to reduce the uncertainties facing human exploration.

The uncertainties facing human exploration of Mars are currently extremely large. The Mars Observer spacecraft, which NASA plans to launch in 1992 and place in Mars polar orbit in late 1993, will provide important new data that would affect planning for further exploration, whether it be robotic or crew-carrying missions. Additional robotic missions that returned rock samples and surveyed more local aspects of Mars would allow mission planners to determine appropriate decision points for undertaking human missions, thereby increasing the probability of mission success.

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[49] Victoria Garshnek, "Exploration of Mars: The Human Aspect," *Journal of the British Interplanetary Society*, vol. 43, 1990, pp. 475-488.

[50] Initial information on psychological risks could be obtained from relatively inexpensive experiments on Earth in inhospitable geographical regions.

[51] Many of these tests could also be done on Earth. Antarctica and many desert environments provide excellent testbeds.

[52] David Scott, Scott Science and Technology, personal communication 1991.

[53] J.F. Santarius and G. L. Kulcinski, "Astrofuel: An Energy Source for the 21st Century," *Wisconsin Professional Engineer*, September/October 1989, pp. 14-18.

Scientists who specialize in the reaction of humans to the space environment also lack basic knowledge of the human reaction to long-term exposure to low and near-zero gravity,[54] as well as the long-term effects of radiation from cosmic rays and solar flares.[55] Information gained by life sciences experiments on space station *Freedom* and *Mir*, or on the lunar surface, could reduce those uncertainties.

Robotics missions will be needed to explore Mars, whether or not the United States decides to land humans on Mars by 2019.

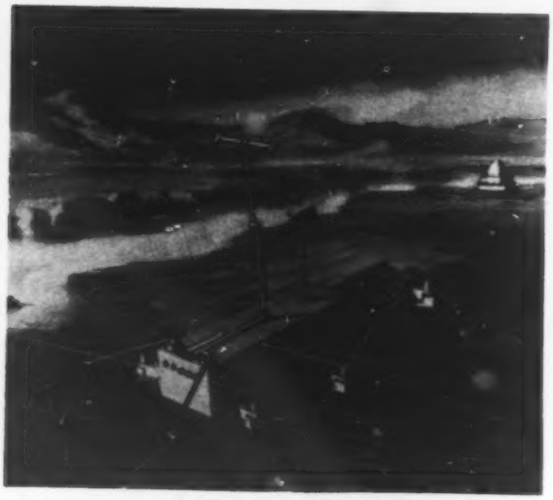

Photo credit: California Institute of Technology, Jet Propulsion Laboratory

Artist's conception of a rover exploring Mars. Overhead, an orbiting satellite relays information from the rover to Earth.

All previous Mars exploration has been carried out by robotic missions. Robotic spacecraft and Mars landers will improve our ability to assess the utility of sending human explorers to Mars, compared to continued exploration by teleoperated means. If the United States decides to send humans to Mars either before or after 2019, robotic missions would be needed to:

1. advance our knowledge of the structure and evolution of Mars by studying its geology, weather, climate, and other physical and chemical characteristics — scientists also need to improve their knowledge of Mars in order to determine what role humans should play when they reach the planet;
2. reduce the risks and costs of human exploration by improving our knowledge of the planet;
3. resolve issues of soil toxicity;
4. resolve issues of possible contamination of Mars by Earth organisms and Earth by any organisms from Mars;
5. refine the planning and design of human missions — how long people should stay on the surface and what tools and robotic support they might need; and
6. identify and characterize a selection of potential landing sites.

If the United States decides to send human crews to Mars, A&R technologies are likely to provide valuable assistance to those crews while on the Martian surface. A&R technologies could provide:

1. support for field studies;
2. detailed survey before, during, and after human travel;
3. emergency support;
4. surveys of particularly difficult or dangerous regions; and
5. routine data collection.

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[54] Some experts urge the development of nuclear-powered vehicles to reduce the amount of time spent in traveling to and from Mars.

[55] Victoria Garshnek, "Crucial Factor: Human-Safely Extending the Human Presence in Space," *Space Policy*, August 1989, pp. 201-216.

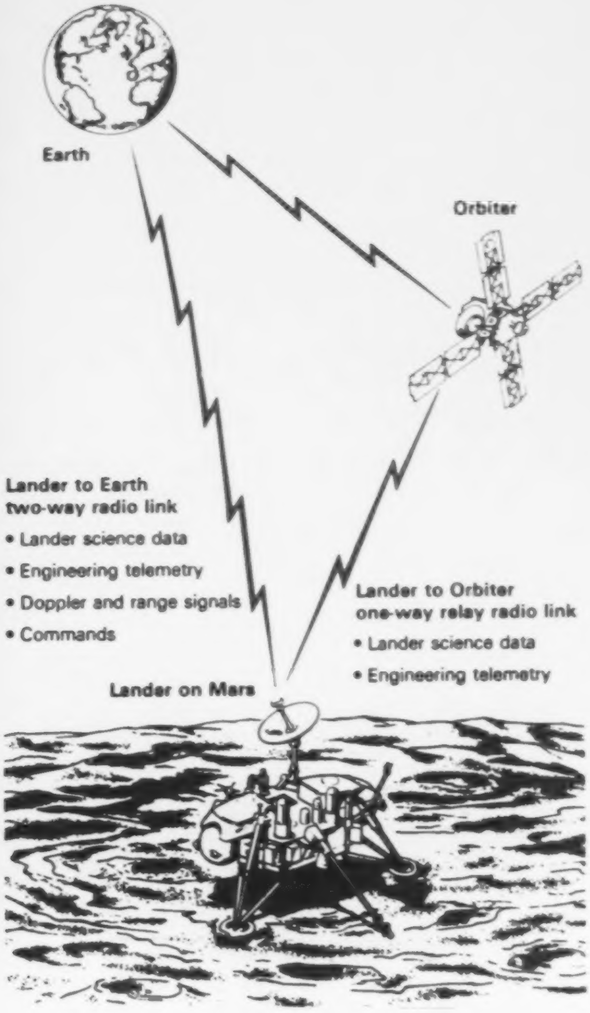

Photo credit: National Aeronautics and Space Administration

The Viking orbiting spacecraft and lander, illustrating the use of robotics technology on Mars. Viking 1 and 2 spacecraft reached Mars orbit in 1975. Each sent a lander to the surface to analyze the soil and report conditions at two locations. The orbiter served to relay information back to Earth.

Although additional information regarding surface conditions on Mars and the tolerance of human systems to microgravity, low gravity, and cosmic radiation would reduce the risks to human life, a round trip to Mars would still carry considerable risk.

Explorers traveling to and from Mars would suffer much higher risk than in returning to the Moon, but would experience greater challenge and adventure. A successful exploratory journey would require the functioning of many different space systems. The United States has relatively little experience in operating and maintaining human habitats in space for long periods. The Soviet Union, in contrast, has supported human crews in low-Earth orbit for periods as long as a year.[56] The United States gained valuable experience in operating the Apollo spacecraft in lunar orbit and on the Moon, at distances of 250,000 miles from Earth. U.S. scientists also gathered information concerning the effects of the space environment on humans during three stays in Skylab in 1973 and 1974, the longest of which lasted 84 days.[57]

However, depending on its relative position with respect to Earth, the distance to Mars varies from 35 to 240 million miles. Round-trip communications delays vary between about 6 to 40 minutes. Depending on the propulsion technology,[58] fuel consumption, and trajectory, a round trip to Mars could take from 1 to 3 years, including stay time on the planet. Neither the United States nor the Soviet Union has supported crew-carrying missions for such long distances and length of time in space. Reducing the risk of an exploratory journey to an acceptable level will require much more data about the planet and human physiology than we now possess, and greater experience living and working in space.[59] The United States and the Soviet Union could both benefit from cooperating on life sciences R&D on risk-reducing technologies.

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[56] A.D. Egorov, A.I. Grigoriev, and V.V. Bogomolov, "Medical Support on Mir," *Space*, vol. 7, No. 2, April/May 1991, pp. 27-29.

[57] W. David Compton and Charles D. Benson, *Living and Working in Space: the History of Skylab*, NASA SP-4208 (Washington, DC: National Aeronautics and Space Administration, 1983).

[58] Chemical propulsion, the only propulsion technology currently available, would require about a year to propel an interplanetary vehicle to Mars. Engineers are exploring the use of nuclear propulsion in order to reduce this time markedly. Synthesis Group, *America at the Threshold* (Washington, DC: The White House, June 1991).

Public reaction to the 1986 loss of *Challenger* demonstrated that there are important qualitative differences between public attitudes toward launching people and launching machines into space. Although human spaceflight helps create interest in space activities, the loss of life in space causes considerable public anguish. If the United States decides to send a human crew to Mars, it will at the same time have to accept the potential for loss of life, either from human error or mechanical failure and increased costs to recover from that loss.[60]

A&R RESEARCH AND DEVELOPMENT

The United States has many promising A&R technologies for use in exploring the Moon and Mars, but to date it has not sufficiently exploited them. At present NASA lacks the robotics capability to carry out a vigorous exploration program using advanced robotics.

Although the sophistication of existing technology is sufficient to carry out moderately sophisticated reconnaissance missions, in many respects, robotic technology is still in its infancy. Hence, using today's projection of future A&R capabilities for space projects two or three decades in the future might aim too low or expect too much.

For example, existing robots show great limitations in their ability to perform mechanically dexterous and flexible tasks. Yet the Japanese have recently demonstrated improvements in the dexterity, flexibility, and compliance of robotic manipulators.[61] U.S. engineers have made important gains in applying the techniques of artificial intelligence to robotic applications.[62] If an integrated A&R program were given sufficient funding, attention, and a common focus, the robotic devices of the early 21st century could be much more capable than those available today.

Despite numerous references in speeches and testimony to the need for robotic technologies in carrying out the exploration of the Moon and Mars, the development of robotic technologies does not receive high priority within NASA. NASA spends about $25 million yearly on applied research in artificial intelligence and robotics as part of its Space Research and Technology program (table 2-2). Yet it devotes relatively little support to A&R development in its Explo-

Table 2-2—NASA's Budget for Space Automation and Telerobotics (thousands of dollars)

	1990 Actual	1991 Budget estimate	1991 Current estimate	1992 Budget estimate
Flight Telerobotics Servicer[a]	79,400	106,300	106,300	55,000
Telerobotics[b]	11,064	13,400	11,045	14,800
Artificial intelligence[b]	11,069	11,600	11,189	13,100
Total	101,533	131,300	128,534	82,900

[a] FTS is funded under space station *Freedom* in fiscal years 1990 and 1991.
[b] Funded under Civil Space Technology Initiative in fiscal years 1990 and 1991.

SOURCE: National Aeronautics and Space Administration, 1991.

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[59] Garshnek, op. cit,. footnote 54, pp. 201-216.

[60] The recovery from the loss of *Challenger* cost the Nation in excess of $15 billion: U.S. Congress, Office of Technology Assessment, *Access to Space: The Future of the U.S. Space Transportation System*, OTA-ISC-415 (Washington, DC: U.S. Government Printing Office, May 1990).

[61] William L. Wittaker and Takeo Kanade, *Space Robotics in Japan* (Baltimore, MD: Japanese Technology Evaluation Center, 1991), ch. 6.

[62] James Hendler, Austin Tate, and Mark Drummond, "AI Planning: Systems and Techniques," *AI Magazine*, summer 1990, pp. 61-77.

ration Technology Program (table 2-3).[63] Prior to fiscal year 1991, NASA spent about $160 million to develop the Flight Telerobotics Services (FTS) for space station *Freedom* (box 2-A), previously NASA's showcase robotics program. However, in January 1991 NASA downgraded the FTS project to a technology demonstration project within the Office of Aeronautics, Exploration, and Technology. Its future is uncertain, but FTS will no longer support space station operations and maintenance.[64] NASA could improve its A&R capabilities and gather useful scientific information by carrying out modest robotics experiments on the Moon.

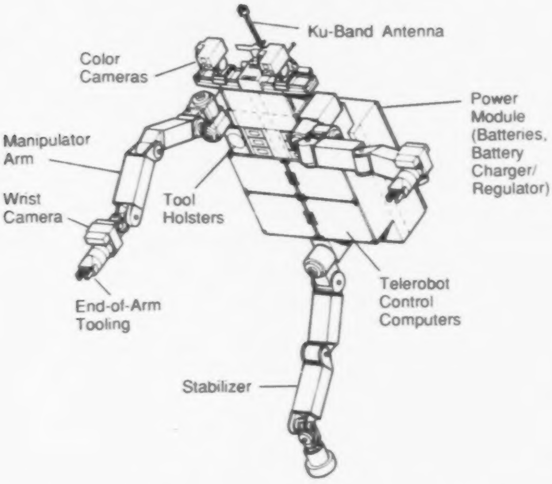

Photo credit: National Aeronautics and Space Administration

Flight Telerobotic Servicer (FTS) device originally planned for use on space station *Freedom* to service and maintain the structure. Technologies planned for the FTS will now be developed and demonstrated by NASA for a variety of space-based uses.

Improving the U.S. approach to A&R technologies will require the collaborative and integrated efforts of industry, academia, and government.

The United States has the capability and the resources to implement a highly competitive A&R program. However, it currently lacks the institutional structure to carry one out. In part this may result from the fact that A&R technologies were oversold in the 1980s. The technologies seemed more simple, tractable, and mature than they were. Continued technology development, and experience with successful systems, could raise public awareness of the utility of A&R systems and create a setting in which A&R engineers can be more innovative in applying them to space and Earth-bound applications.

The potential applications for A&R technologies extend far beyond the space program and include manufacturing and service industries, as well as the defense community. Three conditions

Table 2-3—NASA's Exploration Technology Program (thousands of dollars)

	1990 Actual	1991 Budget estimate	1991 Current estimate	1992 Budget estimate
Space transportation	4,145	38,000	6,000	9,000
In-space operations	1,890	23,000	2,000	–
Surface operations	13,533	62,000	13,800	20,000
Human support	2,330	25,400	3,500	16,000
Lunar and Mars science	570	4,500	700	–
Information systems and automation	–	10,500	–	–
Nuclear propulsion	–	11,000	500	7,000
Innovative technologies systems analysis	–	5,000	1,000	–
Mission studies	5,000	–	–	–

SOURCE: National Aeronautics and Space Administration, 1991.

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[63] About $3.5 million from this budget supports A&R development in fiscal year 1991.

[64] However, both Canada and Japan are pursuing A&R systems for use on *Freedom*.

Box 2-A—The Flight Telerobotic Servicer (FTS)

In the late 1980s, NASA began a program to develop a robotic device to assist in operating, maintaining, and servicing space station *Freedom*. NASA's goals were to:

- reduce space station dependence on crew extravehicular activity;
- improve crew safety;
- enhance crew utilization; and
- provide maintenance and servicing capability for free-flying platforms.

NASA's plans called for two test flights on the space shuttle, with delivery of the final, flight-ready article in 1995. The first test flight would test components of an FTS and would:

- evaluate telerobotic and workstation design approaches;
- correlate engineering measures of performance in space with ground simulation and with analytic predictions;
- evaluate the human-machine interface and operator fatigue; and
- demonstrate telerobotic capabilities.

The second test flight would verify the full FTS for space station work:

- demonstrate capability to perform space station tasks;
- test performance of dual arm manipulator and the attachment, stabilizing, and positioning subsystem;
- test performance of space station FTS orbiter workstation design; and
- develop and verify operational procedures and techniques.

During the congressionally mandated *Freedom* redesign in 1990 and early 1991, the FTS program was transfered from the space station project and is now being reconstituted as a more broadly based technology demonstration project.

NASA expects that much of the technology developed could be applied to applications in manufacturing, hazardous environments, the military, underwater, agriculture, and construction, as well as develop some basic components necessary for lunar and planetary exploration.

SOURCE: National Aeronautics and Space Administration, 1991

constrain the movement of R&D results into applications:

1. A&R R&D is spread among a number of university, industrial, and government laboratories, which by and large communicate poorly with each other about their research progress.
2. Robotics draws on the specialized knowledge of a wide variety of engineering fields; practitioners in each field are often unaware of the approaches and capabilities of another. Hence, they may not work well together. Despite some significant improvements in A&R as a result of interdisciplinary interactions, artificial intelligence and robotics are generally treated as separate disciplines rather than as one overall discipline that focuses on the development of intelligent systems to carry out a variety of well-defined tasks.
3. Existing A&R technologies currently find application only in relatively narrow industrial and government "niches," which have relatively constrained notions of what automation or robotics is. For example, manufacturing concerns make use of robots, but only of the fixed-base

manipulator variety, and in a narrow range of structured tasks. Such robots cannot accommodate unstructured environments.

Because A&R derives from a widely splintered set of subfields, only in weak contact with one another, NASA has a relatively thin technology base upon which to draw for its own needs. Yet OTA's workshop participants expressed the belief that A&R technologies have high potential to make rapid advances if appropriate integrating structures or institutional mechanisms were developed. **An integrated A&R program to serve government needs for planetary exploration and assist industry should engage the capabilities of the universities, government laboratories, and industry.** Such a program might include:

- preferentially funding projects that demonstrate an emphasis on integrating the subdisciplines;
- holding workshops and conferences[65] that stress interdisciplinary sharing, especially between the science and engineering communities, as well as among the various engineering disciplines; and
- developing testbeds to demonstrate prototype technologies and making them available to a wide variety of potential users.

In addition, basic research efforts could be efficiently conducted at the universities. The universities and appropriate government laboratories could refine and demonstrate candidate technologies. Promising systems could then be handed over to development centers and various industries for final development, validation, and implementation. Such an institutional arrangement would create a relatively tight coupling between government laboratories and industry and lead to more efficient transfer into industrial applications and commercial ventures.

COST ESTIMATES

Cost estimates depend critically on the range of planned activities, their schedule, and new information developed in the course of the program. It also depends on knowing what you want to do, when you want to do it, what tools or building blocks are necessary, and what these individual components would cost. Most of these components do not exist today. Hence, it is too early to judge the total costs of an extensive program of Mars exploration that uses either robotic spacecraft or humans.

Very preliminary estimates of returning humans to the Moon and mounting crew-carrying missions to Mars suggest that costs could reach between $300 and $550 billion over a 35-year period, depending on the capabilities desired and the exploration schedule[66] Because the need to support human life in extremely harsh environments leads to large-scale technology development, exploration by human crews may cost as much as 10 to 100 times the costs of robotic exploration.[67] However, comparisons of the costs of carrying out fully robotic or crew-carrying missions can be deceiving because the two kinds of missions would likely accomplish different objectives.

Costs depend critically on the range and scale of planned activities, their schedule, and on a multitude of other factors — some well known, some only dimly perceived, and some as yet totally unrecognized. The ability to predict costs will therefore depend heavily on new information developed in the course of the program. It will also depend on the costs of developing new technologies and manufacturing new systems critical to the success of the various projects within the overall plan. Hence, OTA regards any current estimates as extremely uncertain. Actual costs could be higher or lower depending on progress made in resolving technological hurdles and in reducing the costs of developing new technologies, e.g., a heavy-lift launch system, aerobraking for capture in Mars orbit, space nuclear power, and planetary rovers.

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[65] For example, see Donna S. Pivirotto, "Site Characterization Rover Missions," presented at the American Institute of Aeronautics and Astronautics Space Programs and Technologies Conference and Exhibit, Huntsville, AL, Sept. 25-27, 1990.

[66] General Dynamics Space Systems Division, "Lunar/Mars Initiative Program Options – A General Dynamics Perspective," Briefing Report, March 1990; unpublished estimates developed by NASA for its study entitled, *Report of the 90-Day Study on Human Exploration of the Moon and Mars* (Washington, DC: NASA, November 1989).

[67] Several participants in the OTA workshop, who have experience with space systems, provided this estimate.

Because the costs for any intensive program to return to the Moon and explore Mars will be high, a comprehensive search for cost-reducing methods and techniques will be of high priority.

New technologies may help to reduce the costs of exploring the Moon and Mars. For example, if miniaturized robots were able to provide sufficient capability to carry out scientific studies of Mars, they might make it possible to mount a sample return mission at relatively little cost.[68] Small robots can probably be launched on *Delta* or *Atlas* launch vehicles, which are available today from commercial launch service companies. Because many small robots could be sent to several different locations, they could potentially sample wider regions than a single rover collecting samples from the surface.

However, reducing costs is not just a matter of hardware, but of overall approach and management.[69] For example, where possible, it may be prudent to test major components on lunar missions in order to increase confidence in a Mars flight. Project managers of the Strategic Defense Initiative Organization Delta 180 Project, completed in 1987, found that "decreasing the burden of oversight and review, and delegating authority to those closest to the technical problems, resulted in meeting a tight launch schedule and reducing overall costs."[70] Whether these or similar techniques could lead to reduced costs in a high cost robotic or crew-carrying mission would require careful study. Nevertheless, a number of new technologies and methods, developed for use in manufacturing, may apply to the Mission from Planet Earth.[71]

The operational costs for sending human crews back to the Moon or on to Mars could be very high. As planning for the Mission from Planet Earth proceeds, it will be important for planners to examine carefully the operational costs of each project within the overall plan and determine how best to hold down operational costs.

Operational costs are notoriously hard to judge, as they depend heavily on the success engineers have in developing systems that need relatively little continuing oversight. Experience with the space shuttle[72] and with early design versions of space station *Freedom*[73] suggest that operations costs for crew-carrying spacecraft can be extremely high. For the shuttle, operations costs grew in part because increases in estimated costs and decreases in appropriated funds caused project planners to cut back on spending for subsystems and facilities that would have controlled long-term operations costs by simplifying and automating operational tasks. The shuttle experience demonstrates that near-term cost reductions in some technologies and facilities may lead to higher long-term costs. It also suggests that operations costs can be controlled if the administration and Congress are willing to avoid the temptation to defer expenditures on facilities and new technologies in order to reduce near-term costs. By its nature, however, the development of new technologies carries with it a high degree of technological and financial risk. Therefore, new technologies may well cost more to develop than expected.

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[68] David P. Miller, "MiniRovers for Mars Exploration," *Proceedings of the Vision-21 Symposium*, Cleveland, OH, April 1990.

[69] U.S. Congress, Office of Technology Assessment, *Reducing Launch Operations Costs: New Technologies and Practices*, OTA-TM-ISC-28 (Washington, DC: U.S. Government Printing Office, September 1988).

[70] Ibid., p. 14.

[71] Ibid, p. 4.

[72] U.S. Congress, Office of Technology Assessment, *Reducing Launch Operations Costs: New Technologies and Practices*, OTA-TM-ISC-28 (Washington, DC: U.S. Government Printing Office, September 1988.

[73] William F. Fisher and Charles R. Price, *Space Station Freedom External Maintenance Task Team, Final Report* (Houston, TX: NASA Johnson Space Center, July 1990).

A return to the Moon and the exploration of Mars would have a major impact on NASA's yearly budget, and could adversely affect the funding of NASA's other activities.

Expenditures of $300 to $450 billion even spread over the next 30 years ($10 to $15 billion per year) would require a substantial addition to NASA's yearly space budget, which in fiscal year 1991 equals about $13.4 billion. Over 30 years, a low estimate of $300 billion would average $10 billion (in 1991 dollars), requiring an average 75-percent increase in NASA's fiscal year 1991 budget. Because yearly costs would not generally equal average costs, in some years the costs for the Mission from Planet Earth could be much larger than the rest of NASA's budget, and small perturbations in this funding caused by program delays or technological barriers could overwhelm other, smaller programs.[74] Hence, it may be necessary, e.g., to scale back ambitious plans for a Mission from Planet Earth, or greatly extend the timescale for landing on Mars.

To support the Mission from Planet Earth, as well as the Mission to Planet Earth, the Advisory Committee on the Future of the U.S. Space Program recommended 10-percent annual real growth in NASA's overall budget.[75] Yet, significant pressures on the discretionary portion of the Federal budget would make obtaining a growth rate of 10 percent extremely difficult.[76]

INTERNATIONAL COOPERATION AND COMPETITION

Both international cooperation and competition are important components of a healthy, growing modern economy. As noted earlier, the United States faces a rapidly changing world in which the political and military challenge from the Soviet Union has substantially decreased but the technological and marketing capabilities of Europe and Japan have markedly increased. How the United States invests in its space program could deeply affect other segments of the economy. During the 1990s and perhaps for the first decade of the 21st century, the United States is unlikely to have any competitors in sending human crews to the Moon and Mars. However, we can expect other nations to have a strong interest in developing the technologies required for robotic spacecraft and probes, because these technologies are basic to all space activities. Many of these technologies also have a close relationship with increasing productivity in the manufacturing and service sectors and would greatly enhance later human exploration.

U.S. pursuit of an integrated program of A&R technology would contribute directly to U.S. industrial competitiveness.

Although the United States invented robots and still leads in many areas of research, in other countries robotic technologies have assumed a greater role in the economy. Canada, France, Germany, Italy, and Japan have targeted A&R technologies for development. In some areas, their efforts already exceed U.S. capabilities. The experience gained in applying A&R tasks in space could assist the development of A&R technologies in other parts of U.S. industry and help it to compete in this important arena of the world economy.

Cooperative activities with other countries, if properly structured, could reduce the costs to each participant and increase the return on investment for exploration.

The U.S. space program has a long history of encouraging cooperative activities in space. As noted in an earlier OTA report, "U.S. cooperative space projects continue to serve important political goals of supporting global economic growth and open access to information, and increasing U.S. prestige by expanding the visibility of U.S. technological accomplishments."[77] Cooperative projects also require significant coordination among member nations and cost more overall. Although many cooperative projects have achieved significant scientific success, some, e.g., Ulysses[78] and the international space station *Freedom*, have demonstrated that the management of large cooperative projects may encounter significant financial and other hurdles.[79]

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[74] The ongoing debate over funding space station *Freedom* illustrates the potential effects on smaller programs of funding a single, very large project in NASA's constrained budget.

[75] Advisory Committee on the Future of the U.S. Space Program, op.cit., footnote 3, p. 4.

[76] David Moore, statement before the Committee on Space, Science, and Technology, U.S. House of Representatives, Jan. 31, 1991. Note that 10 percent per year takes 6 years to reach 75-percent overall increase.

A return to the Moon and an exploration of Mars present a range of possible cooperative activities with other nations. Because the costs for intensive planetary exploration are likely to be very high, even for projects that do not require human crews on the Moon or Mars, international cooperative activities could reduce costs to each participant and increase the overall return on investment for exploration. Total program costs are likely to be higher, however, because of the increased cost burden from coordination and management. Yet, except for the Soviet Union, other countries have demonstrated relatively little interest in sending human crews to the Moon or Mars.[80] Based on demonstrated international interest, robotic missions present the strongest opportunities for the United States to initiate cooperative missions, for at least the next decade. All three major space-faring entities — ESA, Japan, and the Soviet Union — might be interested in participating. The Soviet Union has already offered to contribute to a joint project. Just as competition with the Soviet Union to reach the Moon served U.S. cold war goals, cooperation with the Soviet Union today is consistent with our current policy of including them in the family of nations. If the Soviet Union can survive its current economic and political crises, during the early part of the next century, cooperation with the Soviet Union on sending human crews to and from Mars might be attractive.

For example, the Soviet Union has much greater experience than the United States with supporting crews for long periods in space and has conducted numerous experiments in life sciences. **Cooperation with the Soviet Union could markedly reduce U.S. expenditures for life sciences research, which would be extremely important in understanding and reducing the risks of extended spaceflight.**

Japan[81] and Canada[82] have made significant advances in certain areas of A&R germane to space activities. **Entering into a cooperative program to study some of the basic issues of robotics could enhance U.S. progress in developing robotic systems for our space program and for other areas of U.S. industry. By cooperating on basic and preapplication research issues,[83] all partners could advance their own abilities to apply this research to areas of specialized interest, both within the space program and beyond.**

The benefits of international cooperation are closely tied to the methods of implementation.

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[77] U.S. Congress, Office of Technology Assessment, *International Cooperation and Competition in U.S. Civilian Space Activities*, OTA-ISC-239 (Washington, DC: U.S. Government Printing Office, 1985), p. 7.

[78] Ulysses, a project to examine the magnetic fields and other aspects of the solar system far above and below the plane of the solar system, was to have involved two spacecraft, one supplied by the United States and one supplied by the European Space Agency. The project nearly failed in February 1981 when the United States unilaterally withdrew funding for its spacecraft.

[79] See Joan Johnson Freese, *Changing Patterns of International Cooperation in Space* (Malabar, FL: Orbit Book Co., 1990), chs. 7 and 13.

[80] Some Japanese space officials have expressed interest in sending human crews to the Moon, but this interest has not yet been translated into substantial funding support.

[81] William L. Wittaker and Takeo Kanade, *Space Robotics in Japan* (Baltimore, MD: Japanese Technology Evaluation Center, 1991).

[82] NASA Advanced Technology Advisory Committee, "Advancing Automation and Robotics Technolgy for the Space Station *Freedom* and for the U.S. Economy," Technical Memorandum 103851 (Washington, DC: Ames Research Center, National Aeronautics and Space Administration, May 1991), app. C.

[83] As new technologies find their way into industrial or consumer applications, fewer firms wish to share information, as it has a direct bearing on the firm's competitive position.

Experience with other cooperative ventures in space show that to keep costs under control, the planning and engineering interfaces must be kept as simple as possible.[84] The cooperative efforts to study Comet Halley in the mid 1980s worked well, in large part, because the cooperating entities[85] contributed individual projects that each would have pursued even without a cooperative program. Some cooperative projects might require joint development or much closer working relationships than were necessary in studying Comet Halley. Nevertheless, efforts to keep project management as simple as possible should result in more cost-effective results.

The following examples present a few potential cooperative ventures that might contribute to increased U.S. competitiveness and/or U.S. leadership in science and engineering. They represent only a small sample of the range of activities that are possible:

- *Life sciences research* — Cooperating on life sciences work with the Soviets could be highly fruitful for both parties. Soviet scientists are now willing to share more of their data on weightlessness and other life sciences issues and NASA is cooperating with the Soviet Union in a variety of life sciences research, including taking standardized measurements with U.S. equipment onboard *Mir*, and exchanging biological specimens. However, the two countries could extend their opportunities to collect high-quality human data. For example, the United States and the Soviet Union could fly joint long-term missions on the *Mir* space station, using U.S. life sciences and data-recording technology.
- *Astronomy from the Moon* — Making astronomical observations from the Moon might be an especially fruitful area in which to cooperate, at several levels. The major space-faring nations also have strong programs in astronomy and would likely have an interest in cooperating on designing and placing observatories of various sizes on the Moon. Such a program could even involve countries that lack an independent means to reach the Moon.
- *Small rovers on the Moon or Mars* — Rovers are roving instrumental platforms that can extend vision and other human capabilities to distant places. Several small rovers[86] could be developed and then launched on a single booster. Each cooperating entity could build its own small rover, specialized to gather specific data. The redundancy provided by having several robotic devices, independently designed and manufactured, could increase mission success. Here again, each country could contribute according to its own capabilities.
- *Use of Soviet Energia* — The Soviet Union possesses the world's only heavy-lift launch vehicle, capable of lifting about 250,000 pounds to low-Earth orbit. It has offered to make *Energia* available to the United States for launching large payloads. In the near term, the Soviet offer could assist in developing U.S. plans to launch large, heavy payloads, e.g., fuel or other noncritical components of a Moon or Mars expedition. If these cooperative ventures succeeded, they could be extended to include the use of Energia to launch other payloads.
- *Cooperative efforts in network projects* — Europe and the United States are both exploring the use of instrumental networks on Mars to conduct scientific exploration. Each cooperating entity could contribute science payloads, landers, or orbiting satellites to gather data for a joint network project.

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[84] Joan Johnson-Freese, *Changing Patterns of International Cooperation in Space* (Malabar, FL: Orbit Book Co., 1990), ch. 15.

[85] The European Space Agency, Japan's Institute of Space and Astronautical Sciences, NASA, and the Soviet Union's Space Research Institute.

[86] The terms minirover or microrover are often used to denote robotic rovers that range from about a meter down to several centimeters in overall length. Neither term has a precise definition and are often used interchangeably. This report uses the general term small rover.

Chapter 3
Human Exploration of the Moon and Mars

RATIONALE FOR HUMAN EXPLORATION OF THE SOLAR SYSTEM

Should the United States spend public dollars to return to the Moon? Should it consider sending humans to explore Mars? Throughout the latter 20th century, various individuals and groups have urged the establishment of programs to explore the Moon and Mars[1] or other solar system components. They have based their arguments on one or more of the following propositions:

1. establishment of a permanent lunar base or human exploration of Mars would return the United States to a preeminent position in space activities;
2. humans have a fundamental desire to explore the unknown;
3. exploration of Mars would improve U.S. competitiveness;
4. exploration of Mars would vastly improve scientific understanding of the solar system and the Earth; and
5. human exploration of Mars would return other indirect benefits to U.S. society.

1. *Establishment of a permanent lunar base or human exploration of Mars would return the United States to a preeminent position in space activities.* Proponents of this proposition argue for a return to the Apollo goal of U.S. preeminence in space activities across the board in order to demonstrate to the rest of the world and to ourselves that Americans have both the capacity and the will to pursue ambitious technological goals.[2] In this view, demonstrating U.S technological prowess by pursuing a challenging, highly visible goal would result in considerable global geopolitical advantage for the Nation and a return to engineering excellence.

In calling for the United States, to "commit itself to achieving the goal, before this decade is out, of landing a man on the moon and returning him safely to Earth,"[3] President John F. Kennedy in 1961 explicitly sought to use the technological capability of the Nation to establish supremacy in space activities, thereby demonstrating the superiority of the U.S. political and economic system.[4] Then America's primary political and economic competitor was the Soviet Union, which, in orbiting Sputnik in 1957 and cosmonaut Yuri Gagarin in 1961, revealed a surprising level of Soviet technological capability. The Apollo program was successful in demonstrating to the rest of the world that the United States was able to pursue and meet demanding technical challenges.

The global setting for space activities has changed considerably from the days of Apollo when the United States won the race to reach the Moon ahead of the Soviets. The Soviet Union faces major economic and political challenges from within; its allies in Eastern Europe are moving rapidly, if uncertainly, toward market economies and have cut back substantially on military funding. In order to support the movement of the

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[1] One of the earlier attempts to popularize the exploration of Mars was contained in a series of articles in *Colliers* in 1952. In that series, Wernher von Braun, who had helped design the German V-2 rocket and later became the director of NASA's Marshall Space Flight Center, proposed building a large, rotating space station in preparation for a journey to Mars. See also, Wernher von Braun, *The Mars Project* (Champaign, IL: University of Illinois Press, 1991).

[2] National Commission on Space, *Pioneering the Space Frontier: The Report of the National Commission on Space* (New York, NY: Ballentine, 1986), pp. 5-21.

[3] John F. Kennedy, Speech to a joint session of Congress, May 25, 1961.

[4] U.S. Congress, Office of Technology Assessment, *Civilian Space Policy and Applications, OTA-STI-177* (Washington, DC: U.S. Government Printing Office, 1982), pp. 35-36.

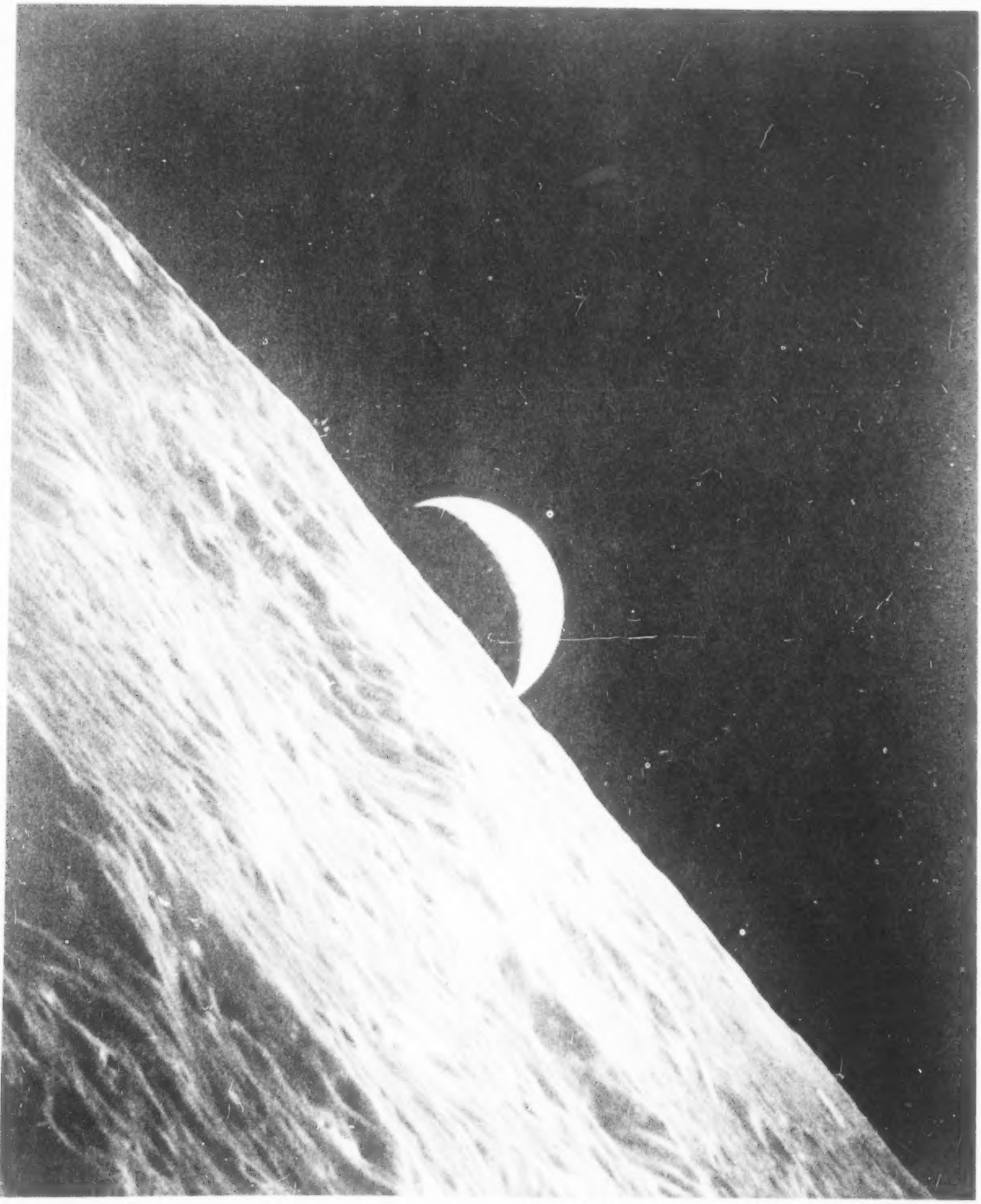

Photo credit: National Aeronautics and Space Administration

Crescent Earth rise above the lunar farside. Photograph taken from Apollo 17 Command Module above the Moon.

former Warsaw Pact allies toward economic stability and growth, the United States has adopted a posture of cooperation in political and economic affairs. For example, during the recent Gulf War, the United States took special care to include the Soviet Union in discussions and decisions regarding U.S. and United Nations intervention. In the recent past, the MidEast has been more an arena for political competition than cooperation with the Soviet Union.

These new events raise the question whether the United States should demonstrate its leadership by human exploration. In the United States other scientific and technical challenges in our national and global agenda, e.g., that of protecting Earth's atmosphere, oceans, and continents from anthropogenic degradation, have assumed greater importance than competing with the Soviet Union in space. It may be, for example, that the United States could better demonstrate technological leadership by tackling and solving major environmental challenges, e.g., the deterioration of the global atmosphere. In recent years, Congress has consistently funded a space program that supported study of the solar system and the universe, Earth's environment, and human exploration, in the belief that all these thrusts, if appropriately balanced, could assist in developing U.S. technological capabilities and demonstrate to the world U.S. leadership in advanced technologies.[5]

2. *Humans have a fundamental desire to explore the unknown.* Some proponents of vigorous exploration missions to Mars base their argument on a perception that sending humans to Mars would satisfy a basic human desire to explore, to push beyond known boundaries,[6] to satisfy our curiosity. These arguments appeal to the imagination and are particularly strong in the United States, where the westward expansion of the last century provides ready metaphors.[7]

These metaphors speak to strongly held notions about the West, supported by the media and popular literature. However, as some historians and folklorists[8] have noted, the use of these metaphors stems from an uncritical view of historical events, and often fail when subjected to analytical scrutiny. Settlement of the western frontier, while contributing to the development of a strong Nation, was also fraught with failures and left many unresolved issues that are still with the Nation.[9] Furthermore, these metaphors are not necessarily shared by all societies. As the historian Stephan Pyne notes, "We explore not because it is in our genetic makeup but because it is within our cultural heritage."[10] In Europe and Japan human exploration of the solar system receives proportionately much less support than in the United States. Japan's and Europe's programs tend to emphasize space science and applications pursued robotically.[11]

Japanese proponents of human spaceflight have urged increased funding for human spaceflight, but with little success. Major attention to human spaceflight would require a concomitant increase in its yearly space budget to develop an adequate launch system[12] and other infrastructure elements for human spaceflight, yet its space budget for both the National Space Development

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[5] Sally K. Ride, *Leadership and America's Future in Space* (Washington, DC: National Aeronautics and Space Administration, August 1987), pp. 11-14.

[6] Arnold D. Aldrich, NASA Office of Aeronautics, Exploration and Technology, "The Space Exploration Initiative," presented to the American Association for the Advancement of Science Symposium on the Human Exploration of Space, Feb. 17, 1990, pp.2-3.

[7] National Commission on Space, *Pioneering the Space Frontier: The Report of the National Commission on Space* (New York, NY: Ballentine, 1986), pp. 3-4.

[8] Beverly J. Stoeltje, "Making the Frontier Myth: Folklore Process in a Modern Nation," *Western Folklore*, vol. 16, No. 4, 1987, pp. 235-255.

[9] See, e.g., Patricia Limmerick, "The Final Frontier?" Excerpted in Brian Dippie, "The Winning of the West Reconsidered," *Wilson Quarterly*, summer 1990, pp. 82-83.

[10] Stephen J. Pyne, "Space: A Third Great Age of Discovery," *Space Policy* vol. 4, No. 3, 1988, p. 189.

[11] Because both entities are interested in pursuing a balanced space program, they have also invested in programs to place humans in space, most done in cooperation with the United States.

[12] Japan is exploring the possibility of developing a space plane, HOPE, but it is to be unpiloted.

Agency and the Institute of Space and Astronautical Science has remained relatively flat as a percentage of gross national product (GNP) over the last 10 years. Japan, with the world's second largest economy, spends only 0.045 percent of its GNP on space activities, compared to about 0.18 percent for the United States.[13]

The picture in Europe varies depending on the country. Nevertheless, each country focuses most of its space investment on space science, space applications, and space transportation.[14] The same is true for the European Space Agency. Although Europe has demonstrated its interest in supporting a human presence in space by contributing to space station *Freedom* and to developing the piloted space plane *Hermes*, its investment in human spaceflight is much less than U.S. investment, both in absolute dollars and as a percentage of its total budget. Europe as a whole spends about 0.11 percent of its GNP on space.

In the Soviet Union, the other nation with a strong program involving human crews, the writings of Konstantin Tsiolkovsky about the colonization of the cosmos served as inspiration to the space program. Tsiolkovsky, who wrote at the end of the 19th century, argued that although Earth provides humanity's cradle, humans cannot live in the cradle forever. Until recently, the accomplishments of the Soviet space program have been used by a succession of Soviet politicians to attempt to demonstrate the technological strength of the Soviet state and the ultimate superiority of the Communist political system. Today, with the failure of communism throughout Eastern Europe and the Soviet Union, and the allied concern over imminent economic collapse, political and popular support for sending humans into space has diminished significantly.[15] Although the Soviet Union plans to study Mars intensively with robotic spacecraft (e.g., the Mars '94 mission), its drive to send humans appears to have subsided.

Nevertheless, whether because of the inherent danger and challenge, or because of an age-old need to create new heroes, human spaceflight captures our interest and stimulates our imagination. For some, it provides inspiration and hope for the future. Some are drawn by the prospect of exploring, and eventually settling, new worlds.[16]

3. *Exploration of Mars would improve U.S. competitiveness.* Some contend that the investment in technology required to return to the Moon to stay and pursue human exploration of Mars would increase U.S. competitiveness and reinvigorate the U.S. economy.[17] Today, the United States faces commercial competition for space markets from Japan and several European countries. China and the Soviet Union have also entered the launch vehicle market with capable launchers.[18]

However, it is not clear that investments in the technologies to support human exploration, which must be supported primarily by public funds, would necessarily contribute to the U.S. competitive position in advanced technologies. Although some technologies developed in the program would have some commercial potential, or would contribute to technological advancement in other areas, many technologies regarded as critical to the Mission from Planet Earth[19] have little use outside it. For example, the heavy-lift launch vehicle is one of the primary technologies needed to support human exploration of the Moon and Mars.[20] Yet a commercial market for heavy-lift launchers is unlikely for decades. Government use would likely be limited to resupply of a space station and sending people to the Moon or Mars.[21] The Soviet Union has been trying to market its heavy-lift launcher, *Energia*, for several years[22] with no success.

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[13] Damon R. Wells and Daniel E. Hastings, "A Comparative Study of the U.S. and Japanese Space Programs," *Space Policy*, in press.

[14] George D. Ojalehto and Richard R. Vondrak, "A Look at the Growing Civil Space Club," *Aeronautics and Astronautics*, February 1991, pp. 12-16.

[15] For example, the Soviet Government has slowed development of the Soviet shuttle, *Buran*, and scaled back plans for a larger version of the Soviet space station, *Mir*. Personal communication, Roald Sagdeev, 1991; Nicholas L. Johnson, *The Soviet Year in Space 1990* (Colorado Springs, CO: Teledyne Brown Engineering, February 1991), pp. 98-122.

[16] See the discussion in Donald P. Hearth (ed.), *Why Man Explores* (Washington, DC: U.S. Government Printing Office, 1977).

[17] Charles Walker, "Remarks to the Scientists' Hearing on Human Mission to Mars," *Journal of the Federation of American Scientists (FAS)*, vol. 44, No. 1, January/February 1991, p. 14.

[18] U.S. Congress, Office of Technology Assessment, *International Cooperation and Competition in Civilian Space Activities, OTA-ISC-239* (Washington, DC: U.S. Government Printing Office, 1985), ch. 4.

[19] Advisory Committee on the Future of the U.S. Space Program, *Report of the Advisory Committee on the Future of the U.S. Space Program* (Washington, DC: U.S. Government Printing Office, December 1990), pp. 30-31.

Aerobraking, nuclear propulsion, space-based engines, and space nuclear propulsion and power, which might be critical to Mars exploration (figure 3-1), and which would be costly to develop, have relatively few applications or market outside

Figure 3-1—Summary of Possible Exploration Technology Needs (Including Robotic and Piloted, Lunar Mars Missions, and Possible Secondary Applications to Other Space Science Missions)

TECHNOLOGY THRUST	TECHNOLOGY PROGRAM AREA	Lunar Outpost		Mars Exploration		Other Solar System Exploration Applications
		ROBOTIC	HUMAN	ROBOTIC	HUMAN	
Earth-To-Orbit	Propulsion, Avionics, Manufacturing		●	⊖	●	◒
Space Transportation	Aerobraking		●	●	●	◒
	Space-Based Engines		●	⊖	●	⊖
	Autonomous Landing		◒	◒	◒	◒
	Auto. Rendezvous & Docking		◒	◒	◒	◒
	Vehicle Structures & Cryo Tankage		⊖	⊖	◒	⊖
	Artificial Gravity				◒	
In-Space Operations	Cryogenic Fluid Systems		◒		◒	
	In-Space Assembly & Construction		◒		◒	⊖
	Vehicle Servicing & Processing		◒		◒	⊖
Surface Operations	Space Nuclear Power	◒	●	◒	●	◒
	In Situ Resource Processing		●	⊖	●	
	Planetary Rover	◒	◒	◒	◒	◒
	Surface Solar Power	⊖	◒	⊖	◒	◒
	Surface Habitats & Construction		◒		◒	
Human Support	Regenerative Life Support		●		●	
	Radiation Protection		●		●	
	Extravehicular Activity Systems		◒		◒	
	Exploration Human Factors		⊖		⊖	
Lunar & Mars Science	Sample Acq. Analysis, & Preserv.	◒	⊖	◒	⊖	◒
	Probes & Penetrators			◒	⊖	◒
	Astrophysical Observatories		◒			⊖
Information Systems & Automation	High-Rate Communications	⊖	⊖	◒	◒	◒
	Exploration Automation & Robotics	◒	◒	◒	◒	◒
	Planetary Photonics	⊖	⊖	◒	⊖	⊖
	Exploration Data Systems	⊖	⊖	◒	◒	◒
Nuclear Propulsion	Nuclear Thermal Propulsion				●	◒
	Nuclear Electric Propulsion				●	◒

LEGEND ⊖ High-Leverage Technology ◒ Enabling for Some Exploration System Options ● Critical Exploration Initiative Technology

NOTE: The symbols under each technology represent NASA's assessment of the relative importance of the technology to the space exploration initiative. However, that assessment and the schedule of development depend critically on the particular exploration scenario chosen.

SOURCE: National Aeronautics and Space Administration, *Space Exploration Initiative Technology Needs and Plans: A Report to the United States Senate Committee on Appropriations Subcommittee on the Veteran's Administration, Housing and Urban Development, and Independent Agencies* (Washington, DC: NASA, summer 1990), p. 3-3.

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[20] Office of Technology Assessment, *Access to Space: The Future of the U.S. Space Transportation System*, OTA-ISC-415 (Washington, DC: U.S. Government Printing Office, 1990), p. 24.

[21] Ibid.

[22] Stephane Chenard, "Restructuring the Soviet Space Industry," *Space Markets*, May 1990, pp. 231-236.

of the Mission from Planet Earth. Others, such as avionics, regenerative life support, and radiation protection would have applications either on Earth or in low-Earth orbit, and could contribute to U.S. competitiveness. Yet, investments in technologies for Mission *to* Planet Earth, or for robotics exploration, are likely to have much greater relevance to the wider American economy, and contribute to U.S. competitiveness with other nations.

4. *Exploration of Mars would vastly improve scientific understanding of the solar system and the Earth.* Many observers have noted that the scientific knowledge gained from a sustained exploration program would assist in understanding the properties of Earth's atmosphere, oceans, and continents.[23] As explained elsewhere in this report, such exploration could help resolve questions regarding the presence of life past or present on Mars, and assist in understanding the long-term evolution of Mars. Questions regarding the origins of life command particular interest, as they relate to the foundations of the human condition.

5. *Human exploration of Mars would return other indirect benefits to U.S. society.* Some argue that the preparations required for sending human crews to and from Mars would capture public interest and spark a revival of interest in the study of mathematics, science, and engineering. They point out, for example, that the Smithsonian National Air and Space Museum has the highest visitation rate of any museum in the world. However, whether such curiosity translates to substantially greater interest among America's young people in pursuing the study of technical subjects has not been demonstrated. As the experience with the Apollo program showed,[24] some percentage of the population will be drawn to devote their life's work to science and technology through encounters with the U.S. space program. However, without accompanying major improvements, in the overall U.S. educational system including greater investment, such interests may not be adequately supported.

The above discussion summarizes several propositions concerning the human exploration of the solar system, and raises questions about the conclusions one could draw from their use. Although proponents often cite one or more of these propositions, they have not been sufficiently analyzed or tested in public or scholarly debate. A survey of the literature on human exploration of the solar system reveals that proponents of expanding the presence of humans beyond Earth orbit have generally relied on the sum of several arguments to support their case.[25] Ultimately, the argument for human exploration of the solar system rests heavily on the proposition that some proportion of humans will eventually wish to establish a home elsewhere in the solar system. Many proponents of a Mission from Planet Earth suggest that such an effort would prepare us for that eventuality.

Although these arguments carry weight in the decisions to explore the solar system, ultimately the broad political process will shape the course of investment in exploration programs, here and abroad, and will include other considerations, e.g., competing demands on the Federal purse. However, the political process is likely to be incapable of allocating resources appropriately if initial cost estimates are incorrect; commitments on capability, schedule, and costs are ignored; and no one is held accountable for cost and schedule growth. In other words, enforcement of performance as promised is central to making the political process work efficiently.

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[23] Carl Sagan and Richard Turco, *Where No Man Thought: Nuclear Winter and the End of the Arms Race* (New York, NY: Random House, 1991), App. C. They point out that research on the consequences to the world's climate of a major nuclear war, the so-called nuclear winter, came about in part because planetary researchers were attempting to understand the evolution of the atmospheres of Venus and Mars.

[24] Thomas Dietz, Laura Lund, and Jeffrey D. Rosendhal, "On the Origins of Scientists and Engineers," Publication of the Space Policy Institute, George Washington University, Washington, DC, April 1989.

[25] See, e.g., Harry L. Shipman, *Humans in Space: 21st Century Frontiers* (New York, NY: Plenum Press, 1989), part I.

RISKS TO HUMAN LIFE IN SPACE

Permanent habitation on the lunar surface or the exploration of Mars would expose humans and other living beings to a wide variety of risks, including possible radiation damage from cosmic rays and solar flare particles and atrophied muscles and loss of bone calcium[26] resulting from extremely low gravity.[27] These risks will have to be understood and mitigation procedures and technologies developed before it will be considered sufficiently safe to commit to such missions. Tables 3-1 to 3-5 summarize the risks to health that crews could experience under different scenarios.

In addition to these physiological risks, crews would also be subject to considerable psychological stress as a result of living for long periods of time in highly controlled, artificial environments. Explorers of earlier eras, though they may have faced loneliness and even cramped traveling conditions, have nevertheless been able to breathe the surrounding atmosphere and walk the Earth or sail the seas in direct contact with their natural environment.[28] Preparing for a Mars expedition would require study of the effects of such environments on the human psyche. It would also require extensive training in order to reduce or mitigate negative psychological effects.

Launch into orbit, travel in space, and return to Earth present additional risk to humans and robots. However, because robots are expendable and can be replaced, their loss is of much less concern than the loss of humans. If the United States wishes to send people into space on a routine basis, it will have to acknowledge and accept the risks of human spaceflight. NASA should exert its best efforts to ensure flight safety but also prepare the public for handling further losses that will likely occur.

THE HUMAN-ROBOTIC PARTNERSHIP

The debate over the exploration of the Moon and Mars is often framed as humans v. robots. Some scientists fear that sending humans to these two celestial bodies might preclude the pursuit of high quality science. On the other hand, some proponents of human exploration evince concern that doing as much science as possible robotically would diminish interest in sending humans. Nevertheless, humans will always be in command. At question is, where would they most effectively stand?

Most participants in OTA's workshop, which was composed of planetary scientists as well as experts in robotics and other disciplines, felt that humans would eventually return to the Moon and reach Mars. Although participants reached varied conclusions regarding the desirability of sending humans, they generally eschewed arguments presented in either/or terms. Rather, participants framed their discussion in terms of the relative strengths of humans and robots in exploring the Moon and Mars. In their view, exploration should be thought of as a partnership to which robots and humans each contribute important capabilities.

For example, robots are particularly good at repetitive tasks. In general, robots excel in gathering large amounts of data and doing simple analyses. Hence, they can be designed for reconnaissance, which involves highly repetitive actions and simple analysis. Although they are difficult to reconfigure for new tasks, robots are also highly predictable and can be directed to test hypotheses suggested by the data they gather. However, robots are subject to mechanical failure, design and manufacturing errors, and errors by human operators.

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[26] Researchers believe that the body recovers fairly quickly from muscle atrophy, but are unsure about the recovery from loss of bone calcium.

[27] The use of artificial gravity on the long journey to and from Mars, or the use of nuclear propulsion, which could significantly shorten it, might circumvent some problems with near zero gravity.

[28] A clear exception, of course, are the many undersea explorers who, for short periods, have lived in comparatively cramped conditions in artificial environments.

People, on the other hand, are adept at integrating and analyzing diverse sensory inputs and in seeing connections generally beyond the ability of robots, particularly when responding to new information. Humans can respond to new situations and adapt their strategies accordingly. Only humans are adept at field science, which demands all of these properties. In the view of several workshop participants, humans would have a clear role in doing geological field work on both celestial bodies and in searching for life on Mars.

Humans are also less predictable than robots and subject to illness, homesickness, stress from confinement, hunger, thirst, and other human qualities. They would need protective space suits and pressurized habitats on both the lunar and Martian surface. Hence, they require far greater and more complicated support than robots.

Placing humans on Mars might lead to a contamination of the Mars environment,[29] complicating the search for indigenous life that might exist in special ecological niches.[30] Conversely, returning humans or soil and rock samples from Mars might contaminate species on Earth, although scientists regard the possibility as extremely remote. Because of these possibilities, however remote in practice, the United States and other signatories to the *Outer Space Treaty* agreed that "State Parties to the Treaty shall pursue studies of outer space, including the moon and other celestial bodies, and conduct exploration of them so as to avoid their harmful contamination and also adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter and, where necessary, shall adopt appropriate measures for this purpose."[31] The initial use of robotic devices, operated by humans on Earth, would make much less impact on the planet than humans and their associated life-support infrastructure, and, as noted, could provide advance information to lessen potential human impacts. In particular, robotic devices could return samples from Mars in such a way that they could be carefully controlled and prevented from contaminating Earth.

The workshop concluded that if humans travel to Mars, their primary role should be to pursue scientific studies. They also concluded that beyond noting the relative strengths and weaknesses of robots and humans in scientific studies, it is too early to assign specific tasks to each through the sequence of exploratory phases. The workshop further concluded that scientists will need to learn more about the planet to determine what robots, and then humans with robots, should do. The relationship between robots and humans is a flexible one, that can shift substantially as more is learned. As robots become increasingly more capable, they can assume tasks now thought too difficult. Improvements in robotic capacity would improve human output as well.

The Moon presents a somewhat different case because it is much closer than Mars. On the one hand, because of the proximity of the Moon, automation and robotics (A&R) engineers can readily overcome the time delay problems they would face in attempting to operate robots at more distant locations. This fact could allow a much more intensive use of teleoperated systems to explore, prospect, experiment with building surface structures and instruments, and operate simple laboratories and observational instruments. Yet because the Moon is closer, it is also technically easier and therefore cheaper to put human crews on the lunar surface than on Mars. Hence, there will remain a great interest in putting people back on the Moon even if robotics engineers develop very capable robotic devices, because some see a permanent base on the Moon as a stepping stone to Mars.

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[29] Although machines can also contaminate new environments, the space agencies make significant attempts to sterilize them before launch.

[30] D.L. De Vincenzi, "Planetary Protection Issues and the Future Exploration of Mars," *Advances in Space Research*, December 1990.

[31] United Nations, *Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and other Celestial Bodies*, 18 UST 2410, Article IX.

Because scientists already know more about sending humans to the Moon than to Mars, the amount of information required from science missions before establishing a human base is far less. However, as noted in the next chapter, the additional data provided from further robotic study of the Moon would reduce risks to humans, and increase their productivity.

Contamination is an issue on the Moon, as large-scale activities that include lunar bases and possibly manufacturing could generate an atmosphere greater than the Moon's existing atmosphere.[32] Not only would such an artificial atmosphere adversely impact scientific study of the Moon's atmospheric sources and sinks, the generation of gases near astronomical observatories could affect their operation.

ROBOTICS SUPPORT OF LUNAR EXPLORATION AND UTILIZATION

If the United States decides to establish a lunar base, A&R technologies would provide critical support to science both prior to sending human crews and after they are on the surface. The partnership between humans and robots could accomplish much more on the surface than humans alone could achieve. In both phases, the lunar surface could provide an important testing ground for A&R technologies that would be used on Mars.

Robotic exploratory missions could:

1. *Advance the basic scientific knowledge of the structure and evolution of the Moon (composition, geology, geophysics, atmosphere)* — Although scientist have gathered significant data about certain aspects of the Moon, the recent lunar observations from the *Galileo* spacecraft[33] have demonstrated scientists' overall knowledge of the lunar surface is surprisingly thin. Detailed survey from orbit with advanced sensors (unavailable in the Apollo days) would enhance the scientific results from human crews should they reach the surface. Robotics Lunar rovers could, for example, explore areas of the Moon that might contain trapped water in advance of placing human crews on the lunar surface.

Photo credit: National Aeronautics and Space Administration

Surveyor IV's footpad on the Moon (Dec. 14, 1967), demonstrating the effects of a small "hop" shortly after landing. The initial resting place of the footpad can be seen to the right of the footpad. This teleoperated test allowed scientists to determine the bearing strength of the lunar surface prior to sending humans.

2. *Assist in selecting landing sites for crews* — Considerable data on potential landing sites on the lunar nearside already exist from Apollo results, yet additional data on the elemental and mineralogical content, compositional diversity, and surface mor-

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[32] Richard R. Vondrak, "Creation of an Artificial Lunar Atmosphere," *Nature*, vol. 248, No. 5450, Apr. 19, 1974, pp. 657, 659.

[33] See the extended abstracts published in *Lunar and Planetary Sciences*, vol. 22, Lunar and Planetary Institute, Houston, TX, 1991: Belton et al., pp. 83-84; Head et al., pp. 547-548; McEwen et al., pp. 871-872; Pieters et al., pp. 1067-1068.

phology for a wide variety of potential sites would be welcome to mission planners and scientists.

3. *Test technologies to be used by human crews in working on the Moon* — A number of technologies, particularly for construction of lunar habitats, could be tested on the Moon prior to human arrival.
4. *Construct habitats or observatories* — Robotic technologies could be used to construct either human habitats or even astronomical observatories and other laboratories prior to the arrival of human crews.

Robotic technologies could assist human crews on the Moon by providing:

1. *Support for field studies* — Detailed exploration of the Moon would require the ability to travel long distances. Robotic rovers could be used to study a variety of locations far from a lunar base. They could assist in detailed field studies using telepresence techniques to give the human operator the sense of being at the site.[34]
2. *Emergency and logistical support* — During an exploration mission, robot vehicles could provide support in the form of emergency assistance or even routine support for mundane tasks and logistics.
3. *Survey of difficult or dangerous regions* — Some regions of the Moon are likely to be particularly risky for human exploration. In such circumstances, robots would essentially act as surrogates for human explorers, and be controlled from a lunar base or from Earth.
4. *Construction support* — Robots could assist human crews in the construction of habitats, laboratories, astronomical observatories, and other structures.

ROBOTICS SUPPORT OF MARS EXPLORATION

If Congress and the administration agree to pursue the human exploration of Mars, robotic technologies would serve two important functions: 1) in addition to supporting the collection of scientific data, they would provide crucial advance information to increase the safety and feasibility of such exploratory missions; and 2) they would support the mission while humans are on the planet. Robotics missions would assist in meeting a set of milestones implied in President George Bush's "long-range continuing commitment" to the exploration of Mars.[35] As in the case of the Moon, the human-machine partnership would greatly extend human capabilities.

Robotic exploratory missions could:

1. *Advance the basic scientific knowledge of the structure and evolution of Mars (geology, weather, climate, etc.)* — Mission planners would need to know a lot more about Mars in order to determine how to maximize the effectiveness of humans when they reach the planet. Robots are particularly adept at reconnaissance, and can be designed to make moderately sophisticated analytical tests of surface soils and rocks.
2. *Reduce the risks and costs of human exploration by improving our detailed knowledge of the planet* — Scientists have relatively poor knowledge of the surface details of Mars. Porous dusts and fields strewn with large blocks may be common.
3. *Resolve issues of soil toxicity and other possible hazards to human safety* — The soil of Mars in the vicinity of the Viking landers turned out to be much more reactive than had been imagined. If breathed into the lungs, Martian soil might adversely affect human health and therefore requires more study before sending humans to the planet.

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[34] Paul D. Spudis and G. Jeffery Taylor, "The Roles of Humans and Robots as Field Geologists on the Moon," in *Proceedings of the 2nd Lunar Base Symposium* (San Diego, CA: Univelt, 1990).

[35] George Bush, "Remarks by the President at 20th Anniversary of Apollo Moon Landing," The White House Office of Press Secretary, July 20, 1989.

4. *Determine possible contamination of Mars by Earth organisms and Earth by any Mars organisms* — If Mars does contain some forms of life, the presence of humans could contaminate them, raising ethical questions regarding the intervention of life from Earth and rendering future scientific study of Mars life forms extremely difficult. Conversely, Mars life forms, if they exist, might potentially harm life on Earth.

5. *Refine planning for the design of human missions* — Robotic technologies could help provide the information necessary to determine what people should do on the surface and what tools and additional robotic support they might need. If humans are to use their capacities to the fullest while on Mars, mission planners and scientists must learn as much as possible about surface conditions on Mars.

6. *Provide data for the selection of potential landing sites 1* — Many types of landing sites exist. It would be important to select and characterize not only relatively safe landing sites, but also those of high scientific interest to maximize the special capacities of humans.[36]

7. *Test technologies to be used by humans in landing or working on the planet* — Numerous technologies, from aerobraking to components of habitats, could be tested by robotic devices prior to the arrival of humans.

Robotic technologies could support human exploration on Mars by providing:

1. *Support for field studies* — Exploring Mars in sufficient detail to contribute substantially to the advancement of knowledge will require the ability to roam far and wide.[37] Robotic instruments could provide humans with greater dexterity and strength, and the ability to project their intellect far beyond their base, thus increasing human productivity and safety. They can also be provided with infrared, ultraviolet, or other sensors beyond the range of the human eye. Although machines are subject to breakdown, when operating properly they are not subject to fatigue and can carry out routine and/or repetitive tasks. Teleoperated mobile robotics devices that could survey local sites and return geological samples to a Mars base for detailed study would be of particular utility. Devices able to provide the additional sense of being at the site (telepresence) might vastly improve human productivity in detailed field studies of the Martian surface.[38]

2. *A detailed survey before human travel* — Prior to sending humans to a region, robotic reconnaissance vehicles could scout a path and explore points of interest for detailed human examination. These instruments need not necessarily be on the surface to be of considerable use. For example, a spacecraft orbiting Mars could be equipped to make detailed, high-resolution images of surface features of interest to scientists prior to visits by human exploration teams.[39]

3. *Maintenance, logistical, and emergency support* — Robotic devices could sharply reduce the amount of routine, mundane tasks human explorers would have to perform. During an exploration mission, robot vehicles could also provide emergency assistance.

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[36] Donna S. Pivirotto, "Site Characterization Rover Missions," presented at the American Institute of Aeronautics and Astronautics Space Programs and Technologies Conference and Exhibit, Huntsville, Alabama, Sept. 25-27, 1990.

[37] For example, if it were located in North America, the Valles Marinaris would extend nearly from the Chesapeake Bay to San Francisco Bay. In places, this "Grand Canyon of Mars" is 16 kilometers deep and 240 kilometers wide. The volcano Olympus Mons is wider at its base than the State of Utah and over 27 kilometers high.

[38] Paul D. Spudis and G. Jeffery Taylor, "The Roles of Humans and Robots as Field Geologists on the Moon," in *Proceedings of the 2nd Lunar Base Symposium* (San Diego, CA: Univelt, 1990); Michael W. McGreevy and Carol R. Stoker, "Telepresence for Planetary Exploration," presented at the SPIE Annual Meeting, Opticon '90," Boston, MA, Nov. 6-9, 1990.

[39] In this regard, such a spacecraft would operate much like the U.S. Landsat or French SPOT Image spacecraft, which carry sensors capable of exploring Earth's surface for minerals. Areas determined to be of particular interest can then be closely examined by field geologists.

4. *A survey of particularly difficult or dangerous regions* — Some regions of Mars are likely to be particularly risky for humans. In such circumstances, robots would essentially act as surrogates for human explorers.

If Congress and/or the administration decide not to pursue the human exploration of Mars in the near term, robotic exploration would nevertheless add to the growing body of scientific data about Mars and prepare the way for any future human exploratory missions. In all, it will be important to determine what is technically and politically possible and what support technologies are needed to accomplish the exploration goals. At present, scientists have only a glimmer of what is possible. For example, although scientists have suggested that telerobotic devices capable of providing a sense of presence would be highly useful,[40] they are only beginning to study how to design, build, and operate such devices effectively.[41]

STRATEGY FOR EXPLORATION

A strategy for planetary exploration will be constrained by scientific knowledge (do we know enough to design a credible work statement?), technological skills and capabilities (do we have adequate space transportation and other supporting systems?), funding (are sufficient public funds available, now and in the future, in competition with other societal needs?), and political support. Workshop participants generally agreed that the pursuit of scientific goals on Mars by itself requires no set time schedule beyond that suggested by resolution of these constraints, available launch windows, and the desire to resolve scientific questions raised by earlier missions. Future missions can be planned as data from missions already in progress are acquired and analyzed. However, several noted that political and programmatic considerations might suggest or even dictate a particular schedule — especially if the political or economic climate changed quickly. For example, when President Kennedy proposed the goal of landing a man on the Moon and returning him, he also selected a date for achieving that goal,[42] with the intention of mobilizing supportive sentiment within Congress, the public, U.S. industry, and NASA.

President Bush also proposed a date, presumably for similar reasons, by suggesting that the United States should plant the American flag on Mars by the 50th anniversary of its landing on the Moon — 2019. Many workshop participants were cautious about the goal of 2019. Although none disagreed that such a goal was technically feasible, at an unknown level of human, economic, and technical risk, many, but not all, felt that given the state of knowledge about Mars, the state of robotic technology, and our state of knowledge about human physiology in space, a specific goal is premature.[43] Scientists simply do not know enough today to assure mission planners that a crew on Mars in 2019 could accomplish a level of useful science or derive other benefits commensurate with the required investment.

If the pursuit of scientific knowledge and insight is the primary reason to explore Mars, and the most important goal of human presence on Mars, then science goals should be optimized on human missions. Proper uses of robotic technologies before and during human missions can accomplish that. A sustained program of robotics missions through the first decade of the next century to set the stage for humans if the United States decides to undertake such an enterprise.

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[40] G. Geffrey Taylor and Paul D. Spudis, "A Teleoperated Robotic Field Geologist," *Proceedings of Space '90 Aerospace ASCE*, Albuquerque, NM, Apr. 22-26, 1990.

[41] Michael W. McGreevy and Carol R. Stoker, "Telepresence for Planetary Exploration," presented at the SPIE Annual Meeting, Opticon '90," Boston, MA, Nov. 6-9, 1990.

[42] NASA officials had previously assured the president that such a goal, though ambitious, was achievable: Letter from James Webb to President Kennedy, May 1961.

[43] Several workshop participants pointed out that setting a challenging schedule, such as President Kennedy set forth for the Apollo program, might motivate the country to achieve difficult tasks, as it did in the 1960s. As noted earlier, however, the national and international political climates are much different today than they were 30 years ago.

MANAGING THE MISSION FROM PLANET EARTH

A program to send humans back to the Moon or to explore Mars would present a formidable challenge to NASA's engineering, scientific, and management capabilities. It would also challenge the Nation's political and fiscal ability to support such a long-term, costly project.

The issue of whether to send humans to the Moon and/or Mars cannot be reduced to scientific and technological considerations alone. The funding and political support for this initiative must be provided over many Presidencies and Congresses. Experience with other large projects in NASA and other agencies suggests that the technical and managerial factors would interact strongly with short- and long-term political and budgetary concerns. These interactions will shape the success or failure of *any* initiative to explore space, whether carried out solely with robots, or with both robots and humans.

Lessons based on experience with the space shuttle[44] and with space station *Freedom*[45] indicate that "success-oriented" planning and the pursuit of incompatible technical goals,[46] which leaves little room for the vagaries of the political process, may lead to much higher than expected costs, and long delays in accomplishing major technical objectives. For example, the space shuttle, which was declared operational in 1982 after four successful flights, still cannot be launched routinely.[47]

A successful strategy for exploring the Moon and Mars would include allowance for the unexpected. The lessons of the space shuttle and space station *Freedom* suggest that the goal of exploring the Moon and Mars could be met most effectively by developing a set of small and large projects, each of which contributes to the larger goal. They also suggest that a successful evolutionary strategy would include the following characteristics:

- *Flexibility* — Planners should not attempt to "freeze" or "lock-in" a large-scale, long-term plan tightly coupled to expected funding. In the case of space station Freedom, each time the budget process resulted in lower appropriated funds for the space station, the program fell into jeopardy. Fiscal and other concerns, including engineering concerns, have made it necessary to rescope the project several times and reorganize its management structure. A more flexible plan would allow investigators to learn from experience, and give them room for changes in scope and project direction, depending on information received and funding available.
- *A set of intermediate, phased goals structured around a common theme* — Previous large-scale civilian space projects have had a highly structured plan with multiple and often incompatible goals.[48] The scale of the Mission from Planet Earth suggests the possibility of generating a set of interim goals with different schedules and measures of success. These interim goals would take into account the rate at which A&R technologies, as well as human capabilities, advance. Planners should resist the tendency to design a large-scale project in order to include every potential user under the aegis of a large program. Instead they should disaggregate the often incompatible goals of mul-

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[44] John M. Logsdon, "The Space Shuttle Program: A Policy Failure," *Science*, vol. 232, May 30, 1986, pp. 1099-1105.

[45] Ronald D. Brunner and Radford Byerly, Jr., "The Space Station Programme," *Space Policy*, vol. 6, No. 2, May 1990, pp. 131-145; Thomas J. Lwein and V.K. Narayanan, *Keeping the Dream Alive: Managing the Space Station Program, 1982-1986*, NASA Contractor Report 4272, National Aeronautics and Space Administration, July 1990; Howard E. McCurdy, *The Space Station Decision: Incremental Politics and Technical Choice* (Baltimore, MD: Johns Hopkins University Press, 1990).

[46] For example, in designing and promoting the space shuttle, NASA attempted to achieve the incompatible goals of piloted spaceflight and inexpensive launches in one vehicle design.

[47] Although all launch systems experience some delays as a result of mechanical failure and weather, the highly complex shuttle has proved to be much more prone to delay, in part because it carries humans. U.S. Congress, Office of Technology Assessment, *Access to Space: The Future of the U.S. Space Transportation System*, OTA-ISC-415 (Washington, DC: U.S. Government Printing Office, 1990).

[48] Critics of the planned space station *Freedom* suggest that because it was designed to be "all things to all people," it serves no constituency well.

tiple constituencies, approaching the goals through multiple small programs, executed either in parallel or in series. Each project or step in the process should provide a useful product independent of the long-term goal. These steps would allow planners to learn from the successes or failures of early projects and factor these lessons into subsequent projects. The knowledge and experience gained in the early stages would allow mission planners to design a far more efficient and safe plan for human exploration than any that could be put forth today or in the near future.

- *A management structure that favors operational experience over planning* — Experience and a judgment about what works best should be the primary test of the succeeding stages in the exploratory process, rather than a plan developed prior to the results of the first stage.

A strategy that had these characteristics would further benefit from the following approaches:

- Optimize each project within the overall goal to achieve a single, highly focused objective.
- Where possible, make each project small enough to locate within a single NASA center in order to give it financial control of the project and to simplify management interfaces. The Exploration Office could play a coordinating role in assuring the relevance of each project to the overall goal. Robotics missions make excellent small projects because they are useful in their own right, demonstrate technology, and give project teams significant operational experience.
- Where possible, make the project's period short enough to provide results before external events undermine its rationale or support.[49]
- Decouple each project from parallel research and development projects insofar as possible within the context of achieving the overall goal, in order to provide a clean test and to clarify responsibility for success or failure.
- Select each project for its centrality to the overall mission through competition with other possible projects.

Successful management of a Mission from Planet Earth will also require stable, consistent funding, and enough of a political commitment from the administration and Congress to carry projects through the inevitable failures as well as through the successes. Congress might wish to consider multiyear funding for certain key projects of the Mission to Planet Earth in order to provide that stability and commitment.

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[49] The many technical and funding challenges to be met in designing and launching large planetary probes make these projects extremely long in scope.

Table 3-1—Medical Consequences From Exposure to Space Flight Factors (Earth Orbit Scenario)

	1 Short-Term, 0–G (1–14 days) **Inflight Problems**	2 **Postflight Problems**	3 Long-Term, 0–G (more than 2 weeks) **Inflight Problems**	4 **Postflight Problems**	5 Artificial Gravity, 1–G (with some level of exercise) **Inflight Problems**	6 **Postflight Problems**
Mainly 0-G/Reduced-G Effects						
Muscle Changes	Muscle strength decreased inflight. Some muscle mass loss indicated. Has not affected mission performance.	Muscle strength decreased (returning to normal in 1–2 wks). Lower extremities show increased susceptibility to fatigue and reduced muscular efficiency. Arm muscles show no change.	Muscle strength decreases. Fatigue noted during EVA. Muscle mass shows indications of decrease but is partially preserved depending on exercise regimen. Inflight exercise reduces strength loss regardless of flight duration.	Increased susceptibility to muscle fatigue. Decreased leg muscle strength. Arm strength normal or slightly decreased. Loss of "muscle pump" contributes to orthostatic intolerance.	No data. Theoretically, muscle strength and mass should be preserved.	No data. Theoretically, postflight muscle fatigue and loss of strength should not occur.
Cardiovascular Deconditioning	Heart rate normal to slightly increased inflight. Isolated cases of nodal tachycardia, ectopic beats, and supraventricular bigeminy.	Heart rate increased postflight, returning to normal by one wk. Resting blood pressure decreased. Orthostatic intolerance (susceptibility to fainting) increased after flights longer than 5 hrs, returning to normal in 3–14 days.	Heart rate normal to slightly increased inflight. Diastolic blood pressure reduced. Premature ventricular beats (PVBs) and occasional premature atrial beats (PABs).	Heart rate increased (normal by 3 wks). Decreased mean arterial pressure. Decreased exercise capacity. Recovery time related to inflight exercise, rather than flight duration. Orthostatic tolerance returning to normal by 3 wks. Unifocal PABs and PVBs.	No data. Theoretically, normal cardiovascular function should be preserved.	No data. Theoretically, postflight cardiovascular problems, including orthostatic intolerance, should not occur.
Bone Loss, Hypercalciuria	Increasing negative calcium balance inflight.	Os Calcis (heel bone) density decreased. Little or no loss from non–weightbearing bones.	Increased potential for kidney stones. Hypercalciuria plateaus after 1 mo. Calcium balance becomes more negative throughout flight.	Decreased density of weight-bearing bones. Recovery time approx. same as flight time. Neg. calcium balance (recovery several wks).	No data. Theoretically, bone integrity should be preserved. Hypercalciuria should not occur. Potential for kidney stones should decrease.	No data. Theoretically, postflight skeletal problems should not occur.
Fluid Shifts, Decreased Fluid/ Electrolyte Levels	Body fluids shift headward causing facial fullness, feeling of head/sinus congestion. Loss of electrolytes persists throughout flight. 3% decrease in total body fluid.	Low body fluid volume contributes to orthostatic intolerance. Conservation of fluid and electrolytes begins immediately upon reaching gravity.	Body fluids shift headward causing facial fullness, feeling of head/sinus congestion. Loss of electrolytes persists throughout flight. 3% decrease in total body fluid. (see short term)	Marked orthostatic intolerance from decreased blood/fluid volume. Recovery of fluids/electrolytes begins immediately upon reaching gravity.	No data. With artificial G, major fluid shifts would not occur. Theoretically, fluid volume would be preserved. Loss of electrolytes should not occur.	No data. Marked orthostatic intolerance from decreased blood/fluid volume should not occur.
Decreased Red Blood Cell (RBC) Mass	RBC mass begins to decrease inflight.	RBC mass decreased. Recovery requires approx. 2 wks.	RBC mass decreases approx. 15% during first 2–3 wks. Partial inflight recovery after 60 days independent of flight duration. Possibility of more acute response to injury/blood loss.	RBC mass decreased. Recovery requires approx. 2 wks to 3 mos following landing. Possibility of more acute response to injury and blood loss.	No data. Theoretically RBC mass should not be affected. However, effects of space factors such as radiation in this scenario are unknown.	No data. Theoretically, postflight problems should not occur.
Neurological Effects	Motion sickness symptoms may appear early in flight and subside/disappear in 2–7 days. Postural illusions, sensations of movement, dizziness, or vertigo may initially occur.	Postflight difficulties in maintaining postural equilibrium with eyes closed. Various vestibular disturbances may be experienced.	Motion sickness symptoms appear early in flight and subside or disappear in 2–7 days. Postural/vestibular illusions may initially occur. Reappearance of illusions during long missions may occur.	Changes in gait, postural disequilibrium especially marked with eyes closed. Observations suggest severity proportional to flight duration and countermeasure use. Additional vestibular disturbances (dizziness, nausea, vomiting) may occur.	Learning to walk and orient in a rotating environment may be challenging. Coriolis force may produce disorientation in certain situations. Severity of problems decrease with increasing radius of rotation.	Transition from rotating to nonrotating environments may result in vestibular and biomechanical readjustment problems initially. Motor/ coordination patterns may need time to readjust to a nonrotating environment.

Table 3-1—Medical Consequences From Exposure to Space Flight Factors (Earth Orbit Scenario) (continued)

	1 Short-Term, 0–G (1–14 days) **Inflight Problems**	2 **Postflight Problems**	3 Long-Term, 0–G (more than 2 weeks) **Inflight Problems**	4 **Postflight Problems**	5 Artificial Gravity, 1–G (with some level of exercise) **Inflight Problems**	6 **Postflight Problems**
Combined 0-G/Reduced-G, Confinement Effects?						
Immune Changes	Although immune system changes do occur (see postflight problems), no serious illnesses have been reported inflight.	Increased number of neutrophils, lymphocyte numbers decreased, returning to normal in 1–2 days. Decreased ability of lymphocytes to respond to challenge.	Decrease in T-lymphocyte numbers with diminished reactivity and capacity for proliferation. Neutrophils increased. Clinical significance unknown but changes may represent potential for contracting viruses, etc. from visiting crews.	Recovery to normal requires 3–7 days. Clinical significance of changes unknown but may represent potential for increased susceptibility to infections, possibly a decreased ability to respond to immunological challenge inherent on Earth.	No data.	No data.
Isolation, Confinement, Remoteness Effects						
Psychological/ Sociological	No consistent sociological problems noted. Some stress may occur as a result of motion sickness or vestibular disturbances.	Some stress may occur as a result of postural/vestibular disturbances.	With increasing duration missions, potential exists for decreased motivation and productivity, compromised crew relations and coordination, and compromised crew/ground relations.	Some stress may occur as a result of postural/vestibular disturbances and general recovery time-course of various body systems.	Some psychological stress may occur in learning to live in a rotating environment.	Some stress may occur in transitioning from a rotating to a non-rotating environment (vestibular and biomechanical readjustments).
Space Environment						
Radiation Exposure	Light flashes in eye observed (radiation striking the retina), but do not interfere with mission performance or crew health. Primary radiation source: inner radiation belt (mainly protons).	No postflight problems noted as a result of short-duration flight radiation exposure.	Possible combined effects with 0-G on physiological systems. Light flashes in eye observed. Possible tissue damage depending on dose and type of radiation encountered. Primary radiation source: inner radiation belt (mainly protons).	Increased potential for cancer induction, cataract formation later in life depending on dose and type of radiation encountered throughout mission.	Artificial G has no effect on dose of radiation encountered. Possibility would still exist for tissue damage depending on dose, duration, and type of radiation encountered.	Artificial G has no effect on dose of radiation encountered. Increased potential would still exist for cancer induction, cataract formation later in life.

SOURCE: Prepared by Victoria Garshnek. References: A.E. Nicogossian, C.L. Huntoon, and S.L. Pool (eds.), *Space Physiology and Medicine*, 2nd ed. (Philadelphia, PA: Lea and Febiger, 1989).

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Table 3-2—Medical Consequences From Exposure to Space Flight Factors (Lunar Outpost Mission) (3-day 0–G transits, 1/6–G surface stay)

	Short-Term (3-day, 0-G transit) **Inflight Problems**	**Long-Duration Surface Stay** (More than 2 wks at 1/6–G)	(Readaptation to 1-G of Earth) **Postflight Problems**
Mainly 0-G/Reduced-G Effects			
Muscle Changes	See column 1, table 3-1	No data. Unknown to what degree 1/6-G would enhance exercise benefits and muscle mass/strength preservation	No data. Unknown if 1/6-G combined with exercise will decrease severity of postflight muscle weakness/loss of efficiency and strength
Cardiovascular Deconditioning	See column 1, table 3-1	No data. Unknown to what degree 1/6-G would influence cardiovascular conditioning when combined with exercise	No data. Unknown how much 1/6-G with exercise would decrease severity of postflight cardiovascular status and severity of orthostatic intolerance (fainting)
Bone Loss, Hypercalciuria	See column 1, table 3-1	No data. Unknown to what degree 1/6-G would enhance exercise benefits for maintaining skeletal integrity and control of hypercalciuria	No data. Unknown to what degree 1/6-G combined with exercise would preserve skeletal integrity and decrease the potential for postflight problems (fractures, etc.)
Fluid Shifts, Decreased Fluid/ Electrolyte Levels	See column 1, table 3-1	No data. Unknown to what degree 1/6-G would influence fluid/electrolyte balance	No data. Unknown if 1/6-G combined with exercise would decrease severity of fluid and electrolytes loss and severity of postflight orthostatic intolerance
Decreased Red Blood Cell Mass	See column 1, table 3-1	No data. Unknown to what degree 1/6-G would influence the partial recovery of RBC mass	No data. Unknown if 1/6-G would influence the time required for full recovery Postflight of RBC mass at 1-G
Neurological Effects	See column 1, table 3-1	No data. Unknown to what degree long-duration 1/6-G would influence locomotion/movement patterns and coordination	No data. Unknown to what degree changes in locomotion/movement patterns and equilibrium would occur and the amount of time needed to readjust to 1-G conditions
Combined 0-G/Reduced-G, Confinement Effects?			
Immune Changes	See column 1, table 3-1	No data. Unknown whether long-duration 1/6-G would significantly influence the immune system	No data
Isolation, Confinement, Remoteness Effects			
Psychological/ Sociological	See column 1, table 3-1	No data. Unknown to what degree long-term remoteness from Earth combined with a hostile/dangerous environment would influence psychological well-being and sociological behavior	No data
Space Environment			
Radiation Exposure	Radiation of free space (beyond Earth's protective radiation belts) encountered. No problems noted previously with Apollo astronauts although Solar Particle Events (SPE) are of concern for future missions (countermeasures and/or shielding needed).	No data on long-term effects of free space radiation on humans. Galactic cosmic radiation and possibility of periodic solar particle events may expose crews to high energy heavy ion particles, protons, electrons, neutrons, x-rays. Effective shielding/shelter and SPE monitoring would need to be provided	No data. Increased potential for cancer induction, genetic mutations, and cataract formation later in life, depending on dose and type of radiation encountered

SOURCE: See table 3-1 for reference list.

Table 3-3—Medical Consequences From Exposure to Space Flight Factors (Mars Mission)
(0-G transits, 1/3-G surface stay scenario)

	Long-Term, Approx. 1 yr (Conventional Propulsion) **Inflight Problems**	Long-Term, Approx. 6 mos (Advanced nuclear propulsion) **Inflight Problems**	**Long-Duration Surface Stay** (More than 2 wks at 1/3-G)	(Readaptation to 1-G of Earth) **Postflight Problems**
Mainly 0-G/Reduced-G Effects				
Muscle Changes	See column 3, table 3-1	See column 3, table 3-1	No data. Unknown to what degree 1/3-G would enhance exercise benefits and muscle mass/strength preservation and/or conditioning after 1-year weightless flight	No data. Severity of postflight muscle weakness/loss of efficiency and strength after 2 years of 0-G unknown. Beneficial effect of 1/3-G exposure unknown
Cardiovascular Deconditioning	See column 3, table 3-1	See column 3, table 3-1	No data. Unknown to what degree 1/3-G would influence cardiovascular conditioning when combined with exercise after a 1-year weightless flight	No data. Severity of postflight cardiovascular status and severity of orthostatic intolerance (fainting) after 2 years of 0-G unknown. Beneficial effect of 1/3-G exposure unknown
Bone Loss, Hypercalciuria	See column 3, table 3-1	See column 3, table 3-1	No data. Unknown to what degree 1/3-G would enhance exercise benefits for maintaining skeletal integrity and control of hypercalciuria after 1-yr 0-G flight	No data. Potential for postflight problems (fractures, etc.) unknown
Fluid Shifts, Decreased Fluid/ Electrolyte Levels	See column 3, table 3-1	See column 3, table 3-1	No data. Unknown to what degree 1/3-G would influence fluid/electrolyte balance after a 1-year weightless flight	No data. Severity of fluid and electrolyte loss and postflight orthostatic intolerance after 2 years of 0-G flight unknown. Beneficial effect of 1/3-G exposure unknown
Decreased Red Blood Cell Mass	See column 3, table 3-1	See column 3, table 3-1	No data. Unknown to what level of recovery 1/3-G would influence RBC mass loss experienced after a 1-year weightless flight	No data
Neurological Effects	See column 3, table 3-1	See column 3, table 3-1	No data. Unknown whether a 1-yr 0-G flight would precipitate significant postflight disequilibrium upon reaching 1/3-G and possible interfere with Mars surface exploration activities initially	No data. Unknown to what degree changes in locomotion/movement patterns and equilibrium would occur (after 2-yrs of 0-G flight and 1/3-G surface stay) and time needed to readjust to 1-G Earth conditions
Combined 0-G/Reduced-G, Confinement Effects?	See column 3, table 3-1	See column 3, table 3-1		
Immune Changes			No data. Unknown whether long-duration 1/3-G would significantly influence the immune system after a 1-year weightless flight	No data
Isolation, Confinement, Remoteness Effects				
Psychological/ Sociological	No data. Unknown to what degree long-term remoteness from Earth combined with a dangerous environment and increasing communication lag-time would influence psychological/sociological behavior.	No data. Unknown to what degree long-term remoteness from Earth combined with a dangerous environment and increasing communication lag-time would influence psychological/sociological behavior	No data. Unknown to what degree long-term remoteness from Earth combined with a hostile/dangerous environment and significant Earth communication lag-time would influence psychological/sociological behavior	No data
Space Environment				
Radiation Exposure	No data on long-term effects of free space radiation on humans. Galactic cosmic radiation and possibility of solar particle events may expose crew to high energy heavy ion particles, protons, electrons, neutrons, x-rays. Shielding/countermeasures needed. Shelter and monitoring for SPE needed.	No data on 6-mo. exposures to free space radiation on humans. Advantage in this scenario is that crew duration/exposure is significantly reduced over the conventional propulsion scenario of 1 yr. Shielding and countermeasures needed during transit. Shelter and monitoring for SPE needed regardless of shortened transit time	No data on long-term physiological effects of Mars radiation environment. Galactic cosmic radiation and possibility of periodic solar particle events may expose crews to high energy heavy ion particles, protons, electrons, neutrons, x-rays. Effective monitoring and shielding strategies would be needed	No data. Increased potential for cancer induction, genetic mutations, and cataract formation later in life, depending on dose and type of radiation encountered throughout mission

SOURCE: See table 3-1 for reference list.

Table 3-4—Medical Consequences From Exposure to Space Flight Factors (Mars Mission) (Artificial-G transits, 1/3-G surface stay scenario)

	Artificial-G Transit (w/exercise) (6-12 mo. depending on Propulsion) **Inflight Problems**	**Long-Duration Surface Stay** (More than 2 wks at 1/3-G)	(Artificial-G Transit/Return to Earth) **Postflight Problems**
Mainly 0-G/Reduced-G Effects			
Muscle Changes	See column 5, table 3-1	No data. Unknown to what degree 1/3-G would induce muscle mass or strength loss. Unknown how beneficial exercise would be to preserve adequate muscle mass and strength in 1/3-G.	No data. Theoretically, return to a 1-G environment during transit should restore any loss in muscle mass or strength induced by reduced gravity of 1/3-G.
Cardiovascular Deconditioning	See column 5, table 3-1	No data. Unknown to what degree 1/3-G could induce cardiovascular deconditioning. Unknown how beneficial exercise would be to preserve desired cardiovascular function.	No data. Theoretically, return to a 1-G environment during transit should restore to normal the cardiovascular deconditioning induced by reduced gravity of 1/3-G.
Bone Loss, Hypercalciuria	See column 5, table 3-1	No data. Unknown to what degree 1/3-G would influence bone integrity. Unknown how beneficial exercise/pharmacological measures would be in preserving skeletal status.	No data. Theoretically, return to a 1-G environment during transit should start the restoration process of any bone mineral loss induced by reduced gravity of 1/3-G.
Fluid Shifts, Decreased Fluid/ Electrolyte Levels	See column 5, table 3-1	No data. Unknown to what degree 1/3-G would influence fluid/electrolyte balance.	No data. Theoretically, return to a 1-G environment during transit should restore any fluid/electrolyte loss induced by reduced gravity of 1/3-G.
Decreased Red Blood Cell Mass	See column 5, table 3-1	No data. Unknown if 1/3-G would induce a level of RBC mass loss.	No data. Theoretically, return to a 1-G environment during transit should restore any RBC mass loss induced by reduced gravity of 1/3-G.
Neurological Effects	See column 5, table 3-1	No data. Unknown to what degree transition from rotating to non-rotating environment would influence locomotion, equilibrium, and coordination initially upon reaching the Martian surface.	No data. Unknown to what degree transition from rotating to non-rotating environment would influence locomotion, equilibrium, and coordination upon reaching Earth's gravity initially.
Combined 0-G/Reduced-G, Confinement Effects?			
Immune Changes	See column 5, table 3-1	No data. Unknown whether long-duration 1/3-G would significantly influence the immune system after a 6-12 month flight in a closed environment.	No data.
Isolation, Confinement, Remoteness Effects			
Psychological/ Sociological	No data. Unknown to what degree long-term remoteness from Earth combined with a dangerous environment and increasing communication lag-time would influence psychological/sociological behavior.	No data. Unknown to what degree long-term remoteness from Earth combined with a hostile/dangerous environment, post-rotation neurological adjustments, communication lag-time would influence psychological/sociological behavior.	No data.
Space Environment			
Radiation Exposure	No data on long-term effects of free space radiation on humans. Galactic cosmic radiation and possibility of solar particle events may expose crew to high energy heavy ion particles, protons, electrons, neutrons, x-rays. Shielding/countermeasures needed. Monitoring and shelter for SPE required.	No data on long-term physiological effects of Mars radiation environment. Galactic cosmic radiation and possibility of periodic solar particles events may expose crews to high energy heavy ion particles, protons, electrons, neutrons, x-rays. Effective SPE monitoring and shielding strategies would be needed.	No data. Increased potential for cancer induction, genetic mutations, and cataract formation later in life, depending on dose and type of radiation encountered throughout mission.

SOURCE: See table 3-1 for reference list.

Table 3-5—Medical Consequences From Exposure to Space Flight Factors (Mars Mission) (0-G and artificial-G abort scenarios)

	0-G Abort (Conventional Propulsion, 2-yrs.) **Inflight Problems**	(Return to Earth) **Postflight Problems**	0-G Abort (Advanced Propulsion, Approx. 1 yr.) **Inflight Problems**	(Return to Earth) **Postflight Problems**	Artif.-G Abort (1-2 yrs., depend on propulsion) **Inflight Problems**	(Return to Earth) **Postflight Problems**
Mainly 0-G/Reduced-G Effects						
Muscle Changes	No data.	No data.	See column 3, table 3-1	See column 4, table 3-1	See column 5, table 3-1	See column 6, table 3-1
Cardiovascular Deconditioning	No data.	No data.	See column 3, table 3-1	See column 4, table 3-1	See column 5, table 3-1	See column 6, table 3-1
Bone Loss, Hypercalciuria	No data.	No data.	See column 3, table 3-1	See column 4, table 3-1	See column 5, table 3-1	See column 6, table 3-1
Fluid Shifts, Decreased Fluid/ Electrolyte Levels	No data.	No data.	See column 3, table 3-1	See column 4, table 3-1	See column 5, table 3-1	See column 6, table 3-1
Decreased Red Blood Cell Mass	No data.	No data.	See column 3, table 3-1	See column 4, table 3-1	See column 5, table 3-1	See column 6, table 3-1
Neurological Effects	No data.	No data.	See column 3, table 3-1	See column 4, table 3-1	See column 5, table 3-1	See column 6, table 3-1
Combined 0-G/Reduced-G, Confinement Effects?						
Immune Changes	No data.	No data.	See column 3, table 3-1	See column 4, table 3-1	See column 5, table 3-1	See column 6, table 3-1
Isolation, Confinement, Remoteness Effects						
Psychological/ Sociological	No data on psychological and sociological aspects of a long-duration abort of a space mission.	No data.	No data on psychological and sociological aspects of a long-duration aborted space mission.	No data.	No data on psychological and sociological aspects of a long-duration aborted space mission.	No data. Some stress may occur in transitioning from a rotating to a non-rotating environment (vestibular and biomechanical readjustments).
Space Environment						
Radiation Exposure	No data on long-term (2-yr) effects of free space radiation on humans. Galactic cosmic radiation and possibility of solar particle events may expose crews to harmful radiation which may exceed recommended limits. Shielding, countermeasures, SPE shelter and monitoring needed.	No data. Increased potential for cancer induction, genetic mutations, and cataract formation later in life depending on dose and type of radiation encountered throughout abort mission.	No data on long-term effects of free space radiation on humans. Galactic cosmic radiation and possibility of solar particle events may expose crews to harmful radiation. Shielding, countermeasures, SPE shelter and monitoring needed.	No data. Increased potential for cancer induction, genetic mutations, and cataract formation later in life depending on dose and type of radiation encountered throughout abort mission.	No data on long-term (2-yr) effects of free space radiation on humans. Galactic cosmic radiation and possibility of solar particle events may expose crews to harmful radiation which may exceed recommended limits (especially in the 2-yr scenario). Shielding, countermeasures, SPE shelter and monitoring needed.	No data. Increased potential for cancer induction, genetic mutations, and cataract formation later in life depending on dose and type of radiation encountered throughout abort mission.

SOURCE: See table 3-1 for reference list.

Chapter 4

Scientific Exploration and Utilization of the Moon

UNDERSTANDING THE MOON

Except for the Sun, the Moon is humanity's most familiar celestial object. Following a complicated apparent path through the night sky, waxing and waning on a 29-day cycle, urging Earth's tidal ebb and flow, the Moon has been the subject of sacred and poetic wonder and scientific examination for millennia. Ancient astronomers tried but despaired of satisfactorily characterizing its complex motions analytically. Galileo contributed to the scientific revolution of the early 17th century by noting from telescopic observations that the Moon had mountains and craters. Because these forms threw shadows as the relative position of the Sun changed, Galileo deduced that the Moon was composed of Earthlike materials[1] — in other words, it could and should be studied like the Earth.[2] Galileo also noted later that although the Moon constantly keeps the same face toward Earth, it also appears to wobble slightly from moonrise to moonset, enabling Earth observers to see somewhat more than 50 percent of the surface.

Through the 18th and 19th century, astronomers examined the Moon with ever greater resolving power as telescopes grew in capability. Early observers took Galileo's suggestion that the Moon was analogous to Earth to the point that they thought it might be habitable and concluded that the Moon might have an atmosphere, great seas, and riverbeds. They named the broad dark places on the lunar surface "Maria," thinking they contained water.

By the 20th century, astronomers understood that Earth's companion had little or no atmosphere and was incapable of sustaining life without major support systems. Beyond generating maps of the visible surface, their primary activity was to catalogue and closely examine lunar craters. Some scientists felt that the many lunar craters resulted from volcanic activity. Others, who argued that the craters came from outside bombardment, saw the heavily cratered Moon as possessing a long-term record of asteroidal and cometary bombardment of the Earth-Moon system. Most astronomers ignored the Moon until the prospect of reaching it with spacecraft became a reality in the 1960s. Not only could astronomers and geologists[3] then view it close up from lunar orbit, including the mysterious farside, but they could look forward to the return of samples for detailed laboratory study on Earth. The geological structure, formation, and evolution of the Moon soon became of great interest, in part because scientists began to recognize that asteroidal or cometary impacts played a significant role in Earth's geological history.[4]

Between 1961 and 1968, the United States sent 28 automated spacecraft to study the Moon, and to select landing sites for automated and piloted landers. Thirteen of these proved unsuccessful. The Soviet Union launched 23 lunar spacecraft between 1959 and 1975 (table 4-1). A Soviet spacecraft, *Luna 2*, became the first to reach the lunar surface on September 12, 1959. *Luna 3* made the first photograph of the farside of the Moon. Although the photograph was extremely crude and indistinct, it and the other Soviet firsts

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[1] Galileo, "The Starry Messenger," in Stillman Drake, Jr., *Discoveries and Opinions of Galileo* (New York, NY: Anchor Books, 1957).

[2] Ray A. Williamson and Philip Chandler, III, "The Promise of Space and the Difference It Makes: The Search for Golden Age," *Cultural Futures Research*, vol. II, No. 2, 1983.

[3] The world's space programs have made possible, among others, the development of the scientific specialty of planetary geology.

[4] This interest accompanied a fundamental change in the scientific understanding of Earth's geological processes with the development of plate tectonic theory.

Table 4-1—Successful Soviet Lunar Missions

Spacecraft	Enounter Date	Mission	Event
Luna 2	Sept. 12, 1959	Moon strike	Struck Moon at 1 W, 30N.
Luna 3	Oct. 10, 1959	Moon flyby	Photos of farside after flyby at 6,200 km.
Zond 3	July 20, 1965	Moon	Passed Moon at 9,200 km. System test; taking pictures, then flew as far as orbital path of Mars.
Luna 9	Feb. 3, 1966	Moon	Soft landed on Moon at 7.1 N, 64.3 W; returned pictures.
Luna 10	Apr. 3, 1966	Moon orbiter	First object to orbit Moon; studied lunar magnetism and radiation.
Luna 12	Oct. 25, 1966	Moon orbiter	Transmitted 15 m resolution pictures of portions of the Moon.
Luna 13	Dec. 24, 1966	Moon	Soft landed on Moon at 18.9 N, 62 W; returned pictures.
Luna 14	Apr. 10, 1968	Moon orbiter	Studied lunar gravitational field.
Zond 5	Sept. 18, 1968	Moon	Circumlunar, recovered, landed Indian Ocean. Man precursor.
Zond 6	Nov. 13, 1968	Moon	Circumlunar, 2,420 km from Moon, Man precursor.
Zond 7	Aug. 11, 1969	Moon	Circumlunar, 2,200 km from Moon, Aug. 11. Man precursor.
Luna 16	Sept. 20, 1970	Moon	Automated return of soil sample to Earth.
Zond 8	Oct. 24, 1970	Moon	Circumlunar, passed 1,120 km of Moon. Man precursor.
Luna 17	Nov. 17, 1970	Moon lander	Landed Lunokhod roving surface vehicle 756 kg, after orbiting Moon.
Luna 19	Oct. 1, 1971	Moon	Orbiter Only. Returned pictures.
Luna 20	Feb. 18, 1972	Moon	Orbited Moon, then soft landed. Sample returner.
Luna 21	Jan. 16, 1973	Moon	Orbited Moon, landed Lunokhod 2 roving laboratory (840 kg) at 26.5 N, 30.6 E.
Luna 23	Nov. 2, 1974	Moon	Orbited Moon, landed at 13.5 N, 56.5 E to drill for soil sample. Sample return failed to launch because drill damaged.
Luna 24	Aug. 19, 1976	Moon	Orbited Moon, landed at 21.7 N, 62.2 E to drill sample. Sample return.

SOURCE: National Aeronautics and Space Administration.

made an important political point and spurred U.S. efforts to best Soviet accomplishments. The first U.S. spacecraft to come near the Moon was *Pioneer 4*, which passed within 37,300 miles in March 1959, but the United States proved unable to reach the Moon with a functioning spacecraft before *Ranger 7*[5] returned more than 4,000 photographs of the lunar surface before crash landing in the Ocean of Storms on July 28, 1964.

THE APOLLO PROGRAM

The U.S. lunar research effort carried out as part of the Apollo program has provided lunar scientists with a rich source of data about the Moon and its physical processes that enhance our scientific knowledge of the origins and evolution of the solar system (box 4-A). These data have vastly improved our scientific understanding of the Moon and its evolution. The United States had planned from the first years of National Aeronautics and Space Administration (NASA) the Ranger series of automated lunar probes to photograph the Moon's surface up close and the Surveyor series to make soft landings, photograph their surroundings and return data on the surface properties. When President John F. Kennedy announced the Apollo program in May 1961, NASA restructured these science programs to support the effort to place humans on the Moon. Robotic spacecraft prepared the way for the first footprints on the Moon.

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[5] *Ranger 1* through *Ranger 6* failed for a variety of reasons. See R. Cargill Hall, *Lunar Impact: A History of Project Ranger* (Washington, DC: U.S. Government Printing Office, 1977), for a detailed history of these spacecraft and their builders.

Robotic Spacecraft

- *Ranger* — The Ranger series[6] was designed to photograph selected areas of the Moon at many different resolutions as the spacecraft sped toward a crash landing on the lunar surface. After a long string of launch and other failures, Rangers 7, 8, and 9 took thousands of images of the Ocean of Storms, the Sea of Tranquility, and the Crater Alphonsus (table 4-2).

Box 4-A—Scientific Accomplishments of the Apollo Program

- Carried out in situ geological and geophysical exploration at six landing sites.
- Returned 385 kilograms of rock and soil samples from six landing sites.
- Emplaced six geophysical instrument stations that carried out measurements of seismicity, heat flow, crustal properties, local fields and particles, and other phenomena.
- Carried out orbital remote sensing experiments, collecting data on crustal composition, magnetic fields, gas emission, topography, subsurface structure, and other properties.
- Obtained extensive photographic coverage of the Moon with metric, panoramic, multispectral, and hand-held cameras during six landing and three nonlanding missions.
- Carried out extensive visual observations from lunar orbit.
- Visited and retrieved parts from Surveyor III, permitting evaluation of the effects of 31 months' exposure to lunar surface conditions.
- Carried out extensive orbital photography of the Earth with hand-held and hard-mounted multispectral cameras, providing verification of Landsat multispectral concept.
- Emplaced laser retroreflectors at several points on the lunar surface, permitting precision measurement of lunar motions with an accuracy of several centimeters.
- Emplaced first telescope on the Moon, obtaining ultraviolet photographs of the Earth and various celestial objects.
- Obtained samples of the Sun by collecting solar wind-implanted ions with surface-emplaced aluminum foil.
- Carried out astronomical photography from lunar orbit.
- Carried out cosmic ray and space physics experiments on lunar surface, in lunar orbit, and in Earth-Moon space.

SOURCE: Paul D. Lowman, Jr., NASA Goddard Space Flight Center, 1991.

[1] Includes only Apollo missions; Gemini, Skylab, and Apollo-Soyuz mission results not included.

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[6] *Ranger 3* through *Ranger 9*. NASA designed *Rangers 1* and *2* to go well beyond lunar orbit to accumulate various data about the space environment between the Earth and the Sun.

Table 4-2—Summary of Ranger Missions

Spacecraft	Launch date	Comments
Ranger I	Aug. 23, 1961	Intended to fly out beyond Moon's orbit for particle and field studies (to 804,500 kilometers). Launch vehicle malfunction placed it in low-Earth orbit (160 kilometers), but spacecraft functioned properly.
Ranger II	Nov. 18, 1961	Identical to Ranger I, with same results.
Ranger III	Jan. 26, 1962	Designed to return pictures of the Moon. Missed Moon and went into heliocentric orbit.
Ranger IV	Apr. 23, 1962	Mission same as Ranger III. Struck back side of Moon; returned no data.
Ranger V	Oct. 18, 1962	Mission same as Ranger II and IV. Missed Moon and entered heliocentric orbit.
Ranger VI	Jan. 30, 1964	Mission to return closeup photos of Moon before crashing into surface. No pictures returned.
Ranger VII	July 28, 1964	Mission to return closeup pictures of lunar surface; 4,304 pictures of lunar surface; 4,304 pictures returned of Sea Clouds. First successful Ranger.
Ranger VIII	Feb. 17, 1963	Returned 7,137 pictures of Seas of Tranquility and high land area west of the sea.
Ranger IX	Mar. 21, 1963	Returned 5,814 pictures of Crater Alphonsus and vicinity.

SOURCE: National Aeronautics and Space Administration.

- *Surveyor* — The Surveyor program was designed to test the technology for soft lunar landings, survey potential future landing sites, and return scientific data about surface properties of the Moon. Five out of seven Surveyor spacecraft successfully reached the lunar surface, photographed their surroundings, and, using a teleoperated scoop to acquire surface samples, carried out measurements on chemical composition and mechanical properties of the lunar soil (table 4-3). Among other things, the Surveyor spacecraft tested the bearing strength of the soil[7] and demonstrated that it would support a crew-carrying lander.

- *Lunar Orbiter* — Five Lunar Orbiters provided nearly 100-percent photographic coverage of the Moon at surface resolutions of 1 to 500 meters (table 4-4). Photographic data from the Lunar Orbiters ruled out several sites thought possible for an Apollo landing, as they revealed far too many craters. Precise tracking of the orbiters also yielded measurements of the nearside lunar gravity field, demonstrating the existence of dense concentrations of mass below the lunar surface. These "mascons," as they were dubbed, later had to be taken into account in calculating the orbit of the Apollo lunar landers.

Astronauts on the Moon

Apollo astronauts, supported by extensive geological training[8] and a team of professional geologists in Mission Control, conducted field studies on the Moon, bringing back samples of particular interest for study in laboratories on Earth. The six lunar missions returned a total of 385 kilograms of lunar material.

Astronauts collected surface rocks, but also brought back cores of subsurface lunar material, made by pushing a coring tube into the surface and mechanically drilling to depths of 3 meters at three different places. Analysis of the lunar samples, which are basically similar to rocks on Earth, has shown that some rocks are as old as 4.6

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[7] Astronomer Thomas Gold had postulated that the Moon's constant bombardment by micrometeoroids might have created a thick lunar dust that would make travel by humans or rovers extremely difficult or even impossible. Although the lunar surface contains a significant dust layer, it is compact enough to pose no major hindrance to navigation.

[8] Astronaut Harrison Schmidt, who roamed the Moon on the Apollo 17 mission, holds a Ph.D. in geology. Other astronauts received field training prior to flight.

Table 4-3—Summary of Surveyor Missions

Spacecraft	Launch date	Comments
Surveyor I	May 30, 1966	Successful soft lunar landing in Ocean of Storms. Primarily on engineering test. Returned 11,237 pictures.
Surveyor II	Sept. 20, 1966	During midcourse maneuver, one of three engines malfunctioned, causing spacecraft tumbling. Communications lost 5-1/2 hours prior to impact on Moon southeast of Crater Copernicus.
Surveyor III	Apr. 17, 1967	Successful soft lunar landing in Sea of Clouds. Returned 6,315 pictures. First soil scoop.
Surveyor IV	July 14, 1967	All communications with spacecraft lost 2.5 minutes prior to lunar impact.
Surveyor V	Sept. 8, 1967	Successful soft lunar landing in Sea of Tranquility. Returned over 19,000 pictures. Alpha scattering experiment provided data on composition of lunar soil.
Surveyor VI	Nov. 7, 1967	Successful soft lunar landing in Central Bay region (Sinue Medii). Returned 30,065 pictures. First lift-off from lunar surface moved 2.5 meters to new location for continuing experiments.
Surveyor VII	Jan. 7, 1968	Successful soft lunar landing on ejecta blanket adjacent to Crater Tycho.

SOURCE: National Aeronautics and Space Administration.

Table 4-4—Summary of Lunar Orbiter Missions

Spacecraft	Launch date	Comments
Lunar Orbiter I	Aug. 10, 1966	Returned 207 frames of medium and high resolution of pictures. Commanded to impact Moon on Oct. 29, 1966.
Lunar Orbiter II	Nov. 6, 1966	Returned 211 frames. Commanded to impact Moon on Oct. 11, 1967.
Lunar Orbiter III	Feb. 5, 1967	Returned 211 frames; photographed Surveyor I. Commanded to impact Moon on Oct. 9, 1967.
Lunar Orbiter IV	May 4, 1967	Returned 163 frames. Commanded to impact Moon on Oct. 6, 1967.
Lunar Orbiter V	Aug. 1, 1967	Returned 212 frames. Commanded to impact Moon on Jan. 31, 1968.

SOURCE: National Aeronautics and Space Administration.

billion years, or as old as Earth, but most formed from 4 to 3 billion years ago. Lunar rock samples contain ample oxygen bound in the silicate minerals that form them, but no hydrogen, except for solar-implanted atoms in the regolith. This means that the Moon likely contains very little water.[9] The lunar samples also contain relatively few mineral species compared to rocks on Earth. The astronauts' samples show that the predominant rock in the dark lunar maria is similar to basalt. Missions to the lighter-colored lunar highlands reveal that they contain an exceptionally high abundance (compared to Earth) of a calcium-rich rock called anorthosite, suggesting that the bulk composition of the upper lunar crust is quite unusual by terrestrial standards. The entire surface of the Moon is covered by a fine-grained, fragmented material called regolith, made from repeated meteoroid impacts, which have pulverized and mixed the upper surface. To date, the available data do not allow scientists to confirm or deny whether the Moon was formed at the same time as Earth but separately, or the Earth and Moon were once part of the same planetary body.[10] Study of existing lunar samples continues. As scientists examine the samples with ever more powerful techniques, the samples reveal additional details of the Moon's history.[11]

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[9] The extreme shortage of water on the Moon could have important consequences for human crews, which would have to bring their own water, transport enough hydrogen to make water from oxygen extracted from lunar rocks and Earth hydrogen, or extract hydrogen from the regolith.

[10] Although the question of the origin of the Moon has not been definitively resolved, most lunar scientists favor the theory that the Moon was created when the Earth suffered an impact with a "planetesimal" body roughly the size of Mars, after separation of Earth's core and mantle.

[11] Stuart Ross Taylor, *Lunar Science: A Post-Apollo View* (New York, NY: Pergamon Press, Inc., 1975).

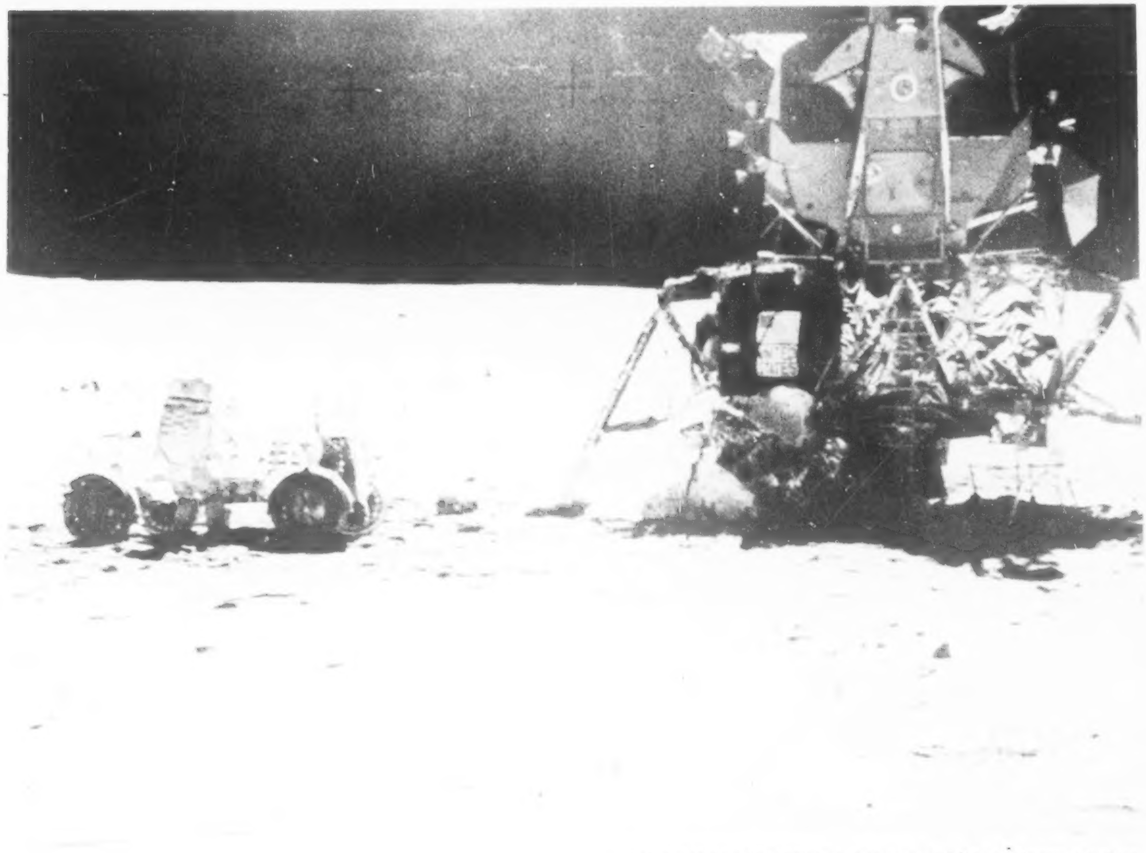

Photo credit: National Aeronautics and Space Administration

Apollo 16 on Moon. Apollo astronaut John W. Young works at Lunar Roving Vehicle on left. Lunar Module at right. Apollo 16 was the fifth NASA voyage to carry people to the Moon.

In addition to doing field geology, and returning lunar samples, each Apollo crew left an experiment package on the Moon[12] that returned data to Earth on lunar seismic activity, the solar wind, the Moon's magnetic field, the lunar atmosphere, and heat flow from the interior. Data from these instruments allowed scientists to detect thousands of moonquakes, measure heat flow, and to estimate the thickness of the lunar crust, but not to confirm the presence or absence of a metallic core.

The crews of Apollo 11, 14, and 15 left laser-ranging reflectors on the Moon that allowed scientists on the Earth to measure precisely the distance between the Earth and the surface of the Moon. Among other things, lunar laser-ranging provided data on the orbital dynamics of the Moon, and demonstrated that the distance between the Moon and Earth is slowly increasing.

Apollo astronauts also took thousands of photographs of the lunar surface from orbit with a variety of cameras. These high-quality photographs constitute some of the highest resolution images of the lunar surface. However, they did not provide complete coverage of the Moon, as they were taken from equatorial orbit. Only about 20 percent of the Moon was under the ground track of Apollo missions. None reached above 30 degrees N (north) latitude. In addition, because Apollo crews focused their efforts on the illuminated portions of the Moon, most of which faced the Earth at the time, they made relatively few observations of the farside. The astronauts also initiated global geochemical/geophysical mapping from orbit, using instruments capable of remotely sensing a small number of elemental constituents and determining the Moon's magnetic properties.

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[12] The Lunar Surface Experiment Package (ALSEP).

The Apollo program provided one important but largely unanticipated benefit to the world—the views of Earth from lunar orbit—which showed it for the first time as a single system. Those photographs also emphasized how vulnerable our planet looks from the outside, and are often used today to convey a sense of Spaceship Earth and global unity.

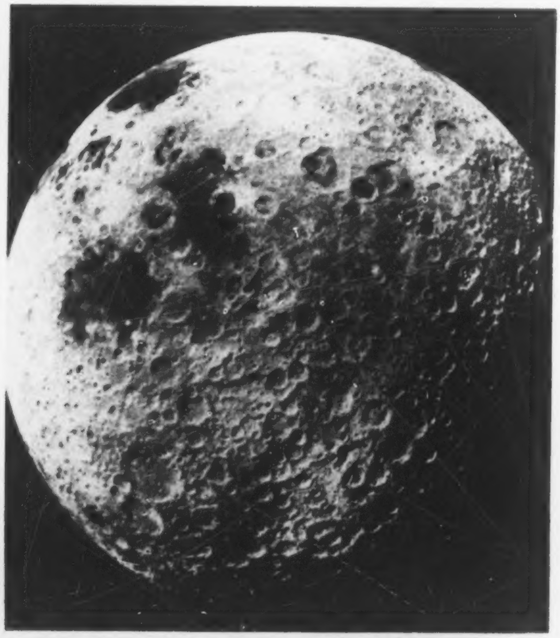

Photo credit: National Aeronautics and Space Administration

Apollo 16 view of a near full Moon on the far side, photographed by the Fairchild Metric Camera from the Apollo 16 Service Module, Feb. 28, 1972.

THE SOVIET LUNAR PROGRAM

In the 1960s and 1970s, the Soviet Union had a strong robotic program aimed at achieving several spaceflight firsts and in gathering scientific data. In addition to launching the first spacecraft to reach the Moon and to photograph the farside of the Moon, the Soviet Union made the first soft landing on the Moon and launched the first lunar orbiter. In 1970, more than a year after the United States landed men on the Moon, the Soviet spacecraft, *Luna 16*, returned soil samples to Earth. Later that year, Soviet engineers successfully landed the Lunokhod rover on the Moon, which became the first rover on a planetary body to be operated from Earth.

The Soviet Union also expended major efforts to land cosmonauts on the Moon, but failed in building the necessary heavy-lift launcher to accomplish the task. Its last mission to the Moon was August 1976, when *Luna 24* landed, drilled a sample of the lunar surface, and returned to Earth with the sample. Although a number of Soviet scientists would like to continue the scientific study of the Moon, study of Venus and Mars have received greater priority in recent years.

SCIENTIFIC OBJECTIVES

Despite the substantial gains made in lunar science during the Apollo program, scientists still have a relatively rudimentary understanding of the Moon, its origins and evolution. Only about 40 percent of the Moon has been imaged at sufficient resolution for scientific study.[13]

The Moon is worth studying for its own sake. But because a substantial portion of Earth's history is closely tied to the history of the Moon, and because Earth and Moon share the same solar system neighborhood, detailed study of the Moon would also assist in understanding the geological[14] and climatological history of Earth. The Lunar Exploration Science Working Group

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[13] When Mars Observer completes its mission in the mid-1990s, Mars will be more completely mapped geochemically than the Moon.

[14] See, e.g., Paul D. Lowman, Jr., "Comparative Planetology and the Origin of Continental Drift," *Precambrian Research*, vol. 44, 1989, pp. 171-195.

(LExSWG)[15] has developed a broad science strategy for the Moon.[16] The following briefly summarizes these scientific themes:

- *Formation of the Earth-Moon system* — Determining the chemical composition of the Moon in comparison to the composition of Earth's mantle would help solve the question of whether the Moon formed from the impact of a giant body with Earth or directly from accretion out of the primordial material. That in turn will affect scientists' understanding of Earth's early history.

- *Thermal and magmatic evolution of the Moon* — The Moon evolved quickly after formation. The Apollo data revealed that the Moon melted early in its history. When it cooled, it formed a low-density crust atop a denser mantle. Some scientists believe that a small metallic core may be present. Because the Moon's volcanic, tectonic, and other geological activity was not vigorous enough to erase the evidence of the Moon's early formation, the lunar crust is likely to provide important clues to the early evolution of Earth, and also Mars and Venus. These planets have experienced enough weathering and geologic activity to erase many obvious signs of their early evolution.

  A survey from orbit using high-resolution spectroscopic sensors will provide estimates of the composition of the lunar crust and its spatial diversity, but understanding its origins will require obtaining samples from the Moon's ancient highlands. Returning samples from the youngest lava flows, as determined by the count of lunar craters in these flows, would provide information about their ages. Seismometers, heat flow probes, and magnetometers on the surface would help determine the Moon's internal structure and thermal properties.

- *Bombardment history of the Earth-Moon system* — Mars, Venus, the Earth, and the Moon all display evidence of bombardment by large and small external objects (meteoroids, comets, and asteroids). Once volcanism ceased on the Moon, bombardment became the primary agent of surface change. Hence, the Moon contains a nearly complete record of its impact bombardment history, from the micrometeoroids that continually pound the surface, to the asteroids that formed the largest craters. Overlapping by the ejected material from successive volcanoes may also have preserved an undisturbed record of the early micrometeoroid influx. In addition to providing insights concerning the numerical density and range of sizes of bombarding objects, the lunar surface contains a statistical record of the like bombardment of Earth.[17] Hence such studies might assist in understanding the periodic extinctions of some species of life on Earth, which some scientists believe result from cometary or asteroidal impacts.[18] Observations from orbit and rock samples from many relatively young craters would provide the necessary data.

- *Nature of impact processes* — Despite considerable progress in studying how and why craters and their deposits form, scientists lack a complete understanding of the dynamics of cratering. High-resolution reconnaissance data from orbit would allow lunar scientists to formulate working hypotheses about the geological evolution of a region, which could be used to guide future sampling studies.

- *Regolith formation and evolution of the Sun* — Regolith, the blanket of broken rock and soil that covers the Moon, results from the impact of external objects with the lunar surface. The impacts both dig up the original surface and redistribute previously created regolithic material. Charged particles from the solar wind and galactic cosmic rays continuously strike the regolith, embedding themselves in it. Thus, the regolith carries a historical record of the Sun and cosmic radiation. Regolith would also provide the material for building a lunar base. Detailed study of the regolith from many different locations at different depths would therefore provide scientists with data about the history of the Sun and add to their understanding of the regolith's potential for use as a construction material. All of the lunar samples returned by the Apollo flights are from the regolith. Although these samples have contributed immeasurably to our knowledge of the lunar surface, they provide only a glimpse of the history of the Sun and of the complicated processes that produce the regolith.

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[15] LExSWG is composed of scientists from NASA, the U.S. Geological Survey, and the universities.

[16] Lunar Exploration Science Working Group, *A Planetary Science Strategy for the Moon*, draft, Sept. 28, 1990.

[17] Richard A.F. Grieve, "Impact Cratering on the Earth," *Scientific American*, April 1990, pp. 66-73.

[18] Walter Alverez and Frank Asaro, "What Caused Mass Extinction?" *Scientific American*, October 1990, pp. 78-84.

More complete understanding will depend on gathering large-scale chemical composition data from a lunar orbiter and detailed chemical and physical study of samples from a variety of sites at several depths. Because the uppermost layers of the regolith react strongly with foreign material e.g., gases, properties of these layers change as soon as they are placed in a spacecraft, which carries with it a variety of gases or gas-producing materials. To study the processes that produce these reactive grains, scientists will likely have to study them in situ at a lunar outpost, where contact with nonlunar gases and other materials can be closely controlled.

- *Nature of the lunar atmosphere* — Contrary to popular belief, which holds that the Moon has no atmosphere at all, the Moon possesses an extremely rarefied atmosphere. Its density, composition, and possible origin are poorly known. The lunar atmosphere is extremely fragile and could be destroyed by significant robotic or human activity.[19] Hence, if this atmosphere is to be studied at all, it will be important to characterize it very early in a program to return to the Moon.

FUTURE ROBOTICS MISSIONS

The Galileo Spacecraft

On its way to make extensive observations of Jupiter, the *Galileo* spacecraft has recently provided stunning observations of parts of the farside of the Moon. *Galileo* was launched toward Jupiter on October 18, 1989, from the shuttle *Columbia*. Because the upper-stage engine used to boost *Galileo* from low-Earth orbit to Jupiter is not powerful enough to take a more direct route, mission scientists have routed Galileo past Venus and the Moon and Earth[20] to benefit from a so-called gravity assist.[21] Galileo passed the Moon on December 8, 1990, allowing mission engineers to check out its sensors and other systems and to provide new data about portions of the lunar surface never examined with multispectral data (box 4-B). Galileo's sensors, which include ultraviolet, visual, and infrared sensors, examined the Orientale Basin, only a portion of which can be seen from Earth, and confirmed the existence of a large farside basin, called the South-Pole Aitken Basin, which could only be inferred from previous data.

Lunar Observer

The first detailed plans for a polar-orbiting spacecraft to survey and analyze the chemical and physical properties of the Moon were developed at the Goddard Space Flight Center[22] and the Jet Propulsion Laboratory[23] in the 1970s. A Lunar observer spacecraft received further impetus in the reports of the Space Science Board's Committee on Planetary and Lunar Explora-

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[19] Richard R. Vondrak, "Creation of an Artificial Lunar Atmosphere," *Nature*, vol. 248, No. 5450, Apr. 19, 1974, pp. 657, 659.

[20] Galileo will pass near Earth again on Dec. 8, 1992.

[21] Charlene M. Anderson, "Galileo Encounters Earth and Venus," *The Planetary Report*, vol. 11, March/April 1991, pp. 12-15.

[22] Goddard Space Flight Center, *Lunar Polar Orbiter Interim Technical Report*, GSFC Report No. X-703-75-141, May 1973.

Box 4-B—Return to the Moon With Robotic Advanced Sensors: Lessons From Galileo

In December of 1990, the *Galileo* spacecraft completed its first flyby of the Earth-Moon system to acquire part of the necessary energy boost for its journey to Jupiter. Although Galileo instruments are optimized for the environment of the outer solar system, and lunar science was not included in original mission objectives, it was recognized that the fly-by geometry would allow several sensors to provide new and unique lunar data. In particular, digital multispectral images could be obtained for the first time for portions of the unexplored lunar farside and the western limb. The scientific focus was expected to center on the multi-ring Orientale Basin, the youngest and exceptionally well-exposed 900-km impact basin on the western limb.

Galileo carries a Solid State Imaging (SSI) camera that uses a CCD (charge coupled device) array detector with seven filters covering the extended visible spectral range (0.4 to 1.0 microns). Even though the fly-by period was brief and relatively small amounts of lunar data were obtained, the Galileo encounter with the Moon had two distinct advantages that allowed this small amount of new data to provide important discoveries. First, from the Apollo and Luna missions we have samples of lunar rocks and soil to analyze in our laboratories. From this "ground truth," we know the composition of several sites on the lunar near side and have identified diagnostic properties of materials that space-borne instruments can detect to provide compositional information for unexplored areas. Second, the geometry of the encounter allowed multispectral images to be obtained for the western nearside, the western limb, and half of the farside. This sequence provided nearside calibration with a direct link to "ground truth" compositional information, which in turn provided a solid interpretative foundation for farside data.

Several surprises were apparent even in preliminary analyses of the Galileo SSI images. The synoptic image of the western limb shown in the opposite photo illustrates one of the most obvious. The Orientale Basin is near the center of the image, the nearside is on the right, the farside on the left. Even the raw data provide evidence for the remarkable basin of the southern farside that is estimated to be twice the size of the Orientale Basin. Two sets of concentric basin rings can be seen on the western edge of the image. The interior of the basin extends to the south pole and is dark, which subsequent photometric analyses show to be due to an inherently low albedo of basin materials. The existence of this huge basin, called the "South-Pole Aitken Basin," was suspected from fragments of earlier information obtained largely during Apollo. The SSI images provide significant new evidence for what is now the largest documented basin on the Moon. Furthermore, compositional analysis of the SSI multispectral data indicates a distinct mineralogical anomaly (enrichment of minerals) associated with the entire South-Pole Aitken basin of the farside.

As the scientific content of these data is analyzed in more detail, some of the obvious lessons of the Galileo encounter are that the lunar crust is quite heterogeneous at all scales and that the lunar samples provide an immense advantage in using data returned from remote sensors with confidence. A more sublime result is that the post-Apollo Moon still contains many surprises waiting detection and recognition with more advanced detectors on robotic spacecraft.

SOURCE: Prepared by Carle Pieters, Brown University, 1991. Authors include M. Belton [Team Leader], C. Anger, T. Becker, L. Bolef, H. Breneman, M. Carr, C. Chapman, W. Cunningham, M. Davies, E. DeJong, F. Fanale, E. Fischer, L. Gaddis, P. Gierasch, R. Greeley, R. Greenberg, H. Hoffmann, J. W. Head, P. Helfenstein, A. Ingersoll, R. Jaumann, T. V. Johnson, K. Klaasen, R. Koloord, A. McEwen, J. Moersch, D. Morrison, S. Murchie, G. Newkum, J. Oberst, B. Paczkowski, C. Pieters, C. Pilcher, J. Pluchak, J. Pollack, S. Postawko, S. Pratt, M. Robinson, R. Sullivan, J. Sunshine, and J. Veverka.

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[23] Jet Propulsion Laboratory, *Mission Summary for Lunar Polar Orbiter,* JPL Doc. 660-41, September 1976.

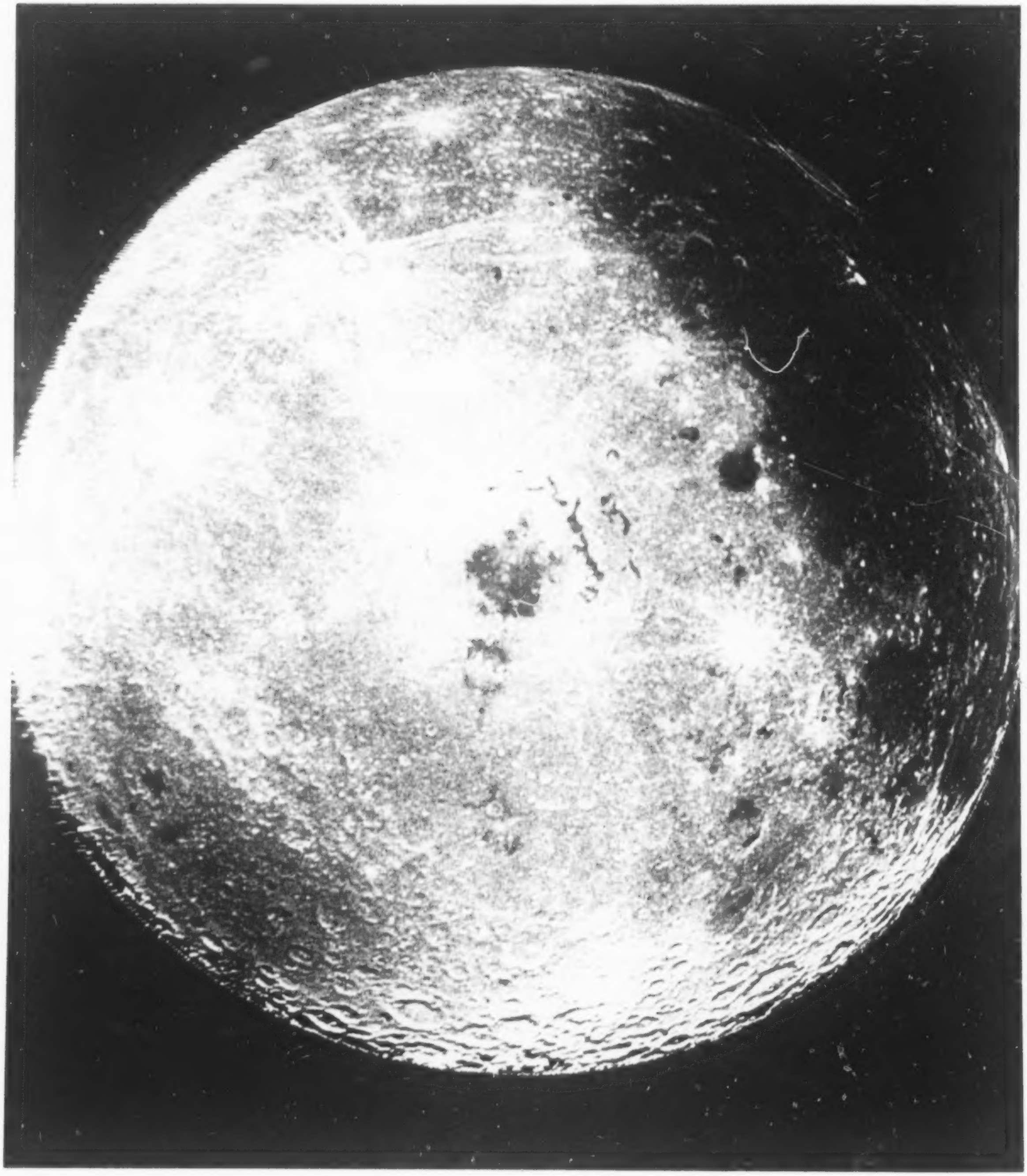

Photo credit: Jet Propulsion Laboratory

Image of the western hemisphere of the Moon taken through a green filter from the *Galileo* spacecraft, Dec. 9, 1990 tion[24] and the NASA Advisory Council's Solar System Exploration Committee.[25]

The focus of scientific objectives and the capabilities of instrumentation for a polar orbiting lunar spacecraft have evolved substantially since the spacecraft was first proposed. Technologies developed over the last two decades allow far more sophisticated global, regional, and local questions to be addressed with advanced sensors. Some of the greatest technical advancements have been in detector technology and electronics. Lunar science provides an excellent application for these technologies—the lunar environment is static and the Apollo samples on Earth provide important "ground truth" information for several areas studied remotely.

NASA had planned to start design work on the Lunar Observer spacecraft (box 4-C) in fiscal year 1991. However, as a result of severe budget pressures, Congress removed $15 million for advanced studies related to Lunar Observer from NASA's planetary exploration budget for fiscal year 1991. NASA used about $1 million to complete spacecraft studies of the relative benefits and drawbacks of using various instruments and configurations for a lunar orbiter.

Other Possible Missions

Various robotics missions to the Moon are now under consideration. These include a network of small instruments, similar to the MESUR probes being studied for Mars, both small and large

Box 4-C—Lunar Observer

Lunar Observer is a proposed spacecraft designed to make detailed compositional and geophysical observations of the Moon's surface from a lunar polar orbit. Data from this spacecraft would constitute the first global assessment of the Moon's composition and surface properties and form the foundation for scientific exploration of the Moon. In addition, data from the Lunar Observer could assist in selecting the best sites for establishing a lunar base or for siting a prototype lunar observatory.

Science Objectives

The following science objectives could be met with the appropriate complement of scientific instruments aboard an orbiting spacecraft:

- estimate the composition and structure of the lunar crust in order to model its origin and evolution;
- determine the origin and nature of the lunar magnetic field and estimate the size of the core;
- estimate the refractory element content of the Moon by measuring the mean global heat flow;
- determine the nature of impact processes over time and how they have modified the structure of the lunar crust;
- determine the nature of the lunar atmosphere and its sources and sinks; and
- assess potential lunar resources.

SOURCE: Lunar Exploration Science Working Group, *A Planetary Science Strategy for the Moon*, draft, Sept. 28, 1990; G.L. Parker and K.T. Nock, "Lunar Observer: Scouting for a Moon Base," presented at the Space Programs and Technology Meeting, Sept. 25, 1990; AIAA paper 90-3781; Office of Technology Assessment.

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[24] National Research Council, Space Science Board Committee on Planetary and Lunar Exploration, *Strategy for Exploration of the Inner Planets: 1977-1987* (Washington, DC: National Academy of Sciences, 1978), pp. 71-74. This study noted the following primary scientific objectives for a lunar polar orbiter: 1) determine global and regional chemistry of the lunar surface; determine global and regional heat flow through the surface; 3) determine whether the Moon has a metallic core and explore its nature.

[25] NASA Advisory Council, Solar System Exploration Committee, *Planetary Exploration Through Year 2000: A Core Program* (Washington, DC: U.S. Government Printing Office, 1983); NASA Advisory Council, Solar System Exploration Committee, *Planetary Exploration Through Year 2000: Scientific Rationale* (Washington, DC: U.S. Government Printing Office, 1988).

rovers, and the emplacement of small astronomical telescopes.

WORKING ON THE LUNAR SURFACE

In his speech of July 20, 1989, President Bush proposed that the Nation return to the Moon "to stay." In other words, the United States should establish a permanently staffed lunar base. Proponents of a lunar base suggest various uses for it:

- *Conduct continued scientific exploration of the Moon* — A lunar laboratory would allow scientists to continue their study of the Moon.[26] Working in the lunar environment would allow much more flexible study of lunar geology and the lunar atmosphere. As noted earlier, scientists on the Moon could use robotic rovers to conduct field research while they supervise the rovers' activities from a protected, underground laboratory.
- *Use the Moon as an astronomical platform* — The Moon would provide a stable, nearly atmosphere-free platform for conducting astronomical research (box 4-D).
- *Use the Moon to learn about living and working in space* — Administration policy calls for expanding the human presence into space. As Earth's nearest neighbor, the Moon provides a stepping stone to Mars and the rest of the solar system.

  On the Moon, scientists could learn more about the human reaction to long-term low gravity (about one-sixth Earth gravity). They could also learn how to work in an extremely hostile environment, building habitats and laboratories, and conducting scientific research about human reactions to lunar conditions. They might also investigate the properties of plants and small animals raised on the lunar surface.
- *Exploit resources found on the lunar surface* — Several individuals have suggested mining the lunar surface for resources to use either in near-lunar space, or to return to Earth. For most resources, the costs of mining the Moon and returning them to Earth would be prohibitive. However, for a resource such as Helium-3,[27] which might eventually find use in fusion reactors, if they ever prove economical,[28] lunar mining might prove worthwhile.[29] If substantial infrastructure were to be placed on the Moon or in near-lunar space, lunar mining would likely be economically preferable to launching material from Earth's surface.[30] However, for the foreseeable future, lunar mining does not seem to be cost-effective.

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[26] G. Jeffrey Taylor and Paul D. Spudis, *Geoscience and a Lunar Base*, NASA Conference Publication 3070 (Washington, DC: National Aeronautics and Space Administration, 1990).

[27] Helium atoms with one less neutron than the vastly more common Helium-4.

[28] U.S. Congress, Office of Technology Assessment, *Star Power: The U.S. and International Quest for Fusion Energy*, OTA-E-338 (Washington, DC: U.S. Government Printing Office, October 1987).

[29] J.F. Santarius and G.L. Kulcinski, "Astrofuel: An Energy Source for the 21st Century," *Wisconsin Professional Engineer*, September/October 1989, pp. 14-18.

[30] For example, the production of oxygen on the Moon to breathe and to use for propellant would quickly become cost-effective for long-term human stays on the surface.

Box 4-D—Advantages and Drawbacks of Using the Moon for Astronomy

Advantages

Compared to sites on Earth or in Earth orbit, the Moon possesses several advantages as a base for pursuing observational astronomical research. The following summarizes the most important ones for optical and radio astronomy. In order to determine the effectiveness of any particular lunar observatory, astronomers would have to make a detailed comparison of advantages, drawbacks, and costs of each proposed system compared to Earth- or space-based alternatives.

- *Ultra-high vacuum.*[1] The virtual absence of an atmosphere on the Moon means that the many atmospheric distortions caused by dust, aerosols, refraction, and scintillation that limit the resolving power of Earth-bound telescopes do not occur. In addition, the near vacuum of the lunar surface would allow telescopes to observe the entire electromagnetic spectrum unencumbered by the absorbing qualities of Earth's atmosphere.
- *Stable solid surface.* The rigidity of the lunar surface and its low incidence of seismic activity (10^{-8} that of Earth) allow relatively simple, low-cost telescope mountings to be used. Those same qualities make possible the construction and operation of interferometers involving many independent radio and optical telescopes. This is particularly important for optical telescopes, as the stability requirements vary inversely with the wavelength of light.
- *Dark sky.*[1] Even the darkest terrestrial night reveals some air glow, which degrades the most sensitive optical measurements. When the Moon is in the night sky, light scattered by Earth's atmosphere interferes markedly with optical observations. Because the Moon has no scattering atmosphere, with proper optical shielding, it should be possible to observe even when Earth and/or the Sun are above the horizon. In contrast, terrestrial telescopes, and those in low-Earth orbits (e.g., the Hubble Space Telescope), collect data only about one-fourth of the time.
- *Cold sky.*[1] Not only does Earth's atmosphere scatter visual light, causing, for example, the sensation of blue sky, it also scatters infrared radiation, including the very long wavelength radiation known as the thermal infrared. This region of the electromagnetic spectrum has become extremely important in recent years, especially for detecting hot regions of star formation, and for very cold stars that are reaching the end of their evolutionary path.
- *Absence of wind.*[1] Protective structures surrounding earthly telescopes must be rigid enough to stand high winds. The absence of wind on the Moon means that structures need carry only static and thermal loads, which would make them much lighter and easier to construct. The lunar equivalent of telescope domes might simply be lightweight, movable foil shades to protect from dust, and from Sun and Earth light.
- *Low gravity*. Because the Moon only has one-sixth of Earth's gravity, lunar structures can be much less massive to carry the weight than Earth-bound structures. The presence of some gravity means that debris and dust fall quickly to the surface rather than tagging along, as they would do in space.
- *Rotation*. The lunar "day," its period of full rotation, lasts approximately 30 Earth days. Such a slow rotation rate allows observers to keep telescopes pointed in the same direction for long periods and permits the long integration rates required for extremely faint sky objects.
- *Distance from Earth.* The 400,000-kilometer distance between the Earth and the Moon weakens the electromagnetic noise generated on Earth by a factor of 100 compared to a radio observatory in geosynchronous orbit. Radio observations on the Moon will be very little affected by radio emission from Earth.
- *Lunar farside.* Despite the distance from Earth, reception in some radio frequencies would nevertheless be affected by noise generated by activities on Earth. The farside of the Moon is permanently oriented away from Earth. Siting a radio telescope on the lunar farside would permit the reception and discrimination of very faint radio signals in some critical radio bands.

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[1] Telescopes in geostationary orbit also share in these advantages.

Continued on next page

Box 4-D—Advantages and Drawbacks of Using the Moon For Astronomy—Continued

- *Useful landforms.* The surface of the Moon has numerous symmetrical craters that would be suitable for use as astronomical telescopes, similar to the world's largest radio telescope—the 300-meter dish at Arecibo, Puerto Rico.
- *Relative absence of competitive uses of the surface.* For a long time, the surface of the Moon is likely to have few competing uses.

Drawbacks

Siting radio and optical telescopes on the lunar surface also possesses major disadvantages compared to space-based or Earth-based systems. Many of these disadvantages would fade away if a permanent lunar colony of sufficient size to support astronomy were established for other reasons, e.g., to study the long-term effects of low gravity conditions on humans, or to support lunar mining. In addition, if robotic emplacement were to prove cost-effective, these drawbacks would also diminish.

- *Distance from Earth.* The great distance from Earth to the Moon would make logistics and repair more difficult and therefore much more costly.
- *High projected costs.* Providing transportation to and from the Moon for people and equipment would be extremely costly. In addition, the costs of establishing a lunar base and constructing observatories in the hostile lunar environment would be great. As lunar crews became more accustomed to working on the Moon, the latter costs would likely decrease.
- *Potential for competing systems.* Some of the advantages of a lunar observatory also apply to telescopes situated in geostationary orbit. In addition, spacecraft designers have more than two decades experience designing and building spacecraft that operate in geostationary orbit. Telescopes located in geostationary orbit would likely compete economically with telescopes located on the Moon. The highly successful International Ultraviolet Explorer (IUE) provides a clear example of such economic competition. IUE was built at a cost (1991 dollars) of about $ 250 million and launched in 1978. It still provides high-quality ultraviolet data for hundreds of astronomers per year.
- *Unknown practical details.* Living and working in space has always been much more difficult and costly than foreseen when systems are planned. The lunar surface is unlikely to be different.
- *Cosmic ray protection.* Earth's magnetic field protects its surface and near-Earth space from cosmic rays and particles from the solar wind. The Moon has no such field. Hence, both instruments and humans need to have special protection from these highly damaging particles.[2]
- *Micrometeoroid protection.* Sensitive surfaces, e.g., optical mirrors, will have to be protected from the damaging impacts of micrometeoroids that constantly rain down on the lunar surface. However, spacecraft in low-Earth orbit suffer from the effects not only of micrometeoroid material, but also artificial orbital debris.[3]
- *Need for substantial habitats for human operators.* Humans will need pressurized quarters for living and working on the Moon. They will also need considerable protection from lethal doses of charged particles from cosmic rays and from the occasional solar flare.
- *Lunar dust.* Lunar observatories will need protection from Lunar dust, which, when disturbed, tends to adhere to surfaces with which it comes in contact.

SOURCES: Harlan J. Smith, "Some Thoughts on Astronomy From the Moon," in Michael J. Mumma, Harlan J. Smith, and Gregg H. Linebaugh, *Astrophysics from the Moon*, American Institute of Physics Conference Proceedings, vol. 207 (New York, NY: American Institute of Physics, 1990), pp. 273-282; Jack O. Burns, Nebojsa Duric, G. Jeffrey Taylor, and Stewart W. Johnson, "Observatories on the Moon," *Scientific American*, vol. 262, No. 3, 1990, pp. 42-49; Office of Technology Assessment.

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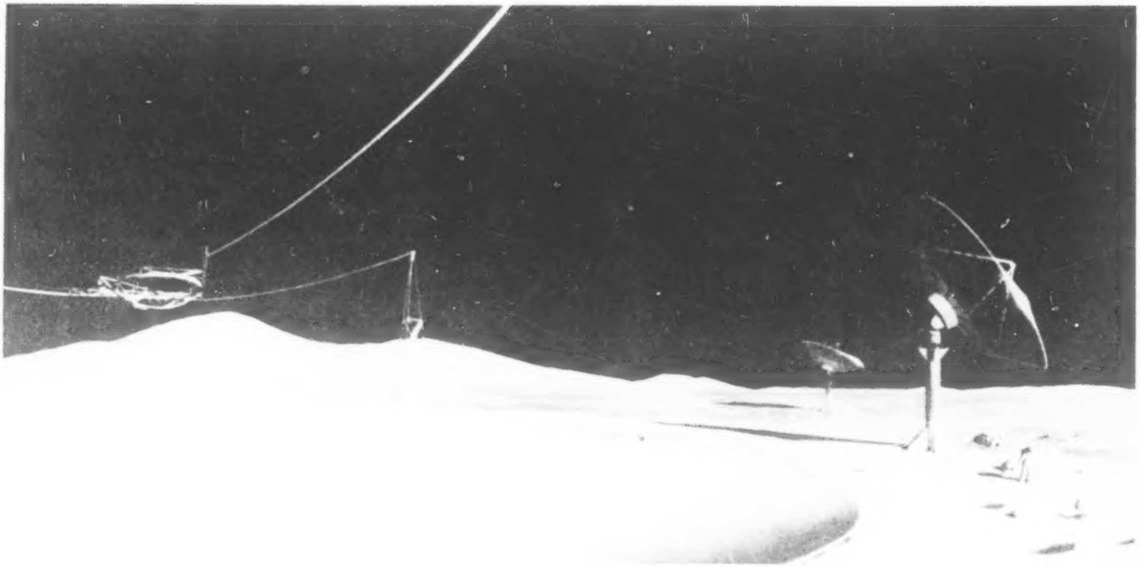
[2] Observatories located in geostationary orbit, which is outside Earth's protective magnetic shield, also require such protection.

[3] U.S. Congress, Office of Technology Assessment, *Orbiting Debris: A Space Environmental Problem*, OTA-BP-ISC-72 (Washington, DC: U.S. Government Printing Office, September 1990).



Courtesy of National Aeronautics and Space Administration

Artist's [illegible] a large radio telescope constructed from a [illegible] is suspended above the radio dish.

Chapter 5
Scientific Exploration of Mars

UNDERSTANDING MARS

The planets have fascinated humankind ever since observers first recognized that they had characteristic motions different from the stars. Astronomers in the ancient Mediterranean called them the wanderers[1] because they appear to wander among the background of the stars. Because of its reddish color as seen by the naked eye, Mars drew attention. It has been the subject of scientific[2] and fictional[3] interest for centuries.[4] In recent years, planetary scientists have developed increased interest in Mars, because Mars is the most Earthlike of the planets. "The study of Mars is [therefore] an essential basis for our understanding of the evolution of the Earth and the inner solar system."[5]

Planetary exploration has been one of the National Aeronautics and Space Administration's (NASA) primary goals ever since the U.S. civilian space program was started in 1958.[6] As the next planet from the Sun beyond Earth, and the subject of intense ground-based observations prior to the first satellite launch, Mars has received particular attention. After sending three Mariner spacecraft on Mars "flybys" in the 1960s,[7] NASA successfully inserted Mariner 9 into an orbit about Mars[8] on November 13, 1971. It was the first spacecraft to orbit another planet (box 5-A). For the first 2 months of the spacecraft's stay in Mars' orbit, the most severe Martian dust storms ever recorded obscured Mars surface features. After the storms subsided and the atmosphere cleared up, Mariner 9 was able to map the entire Martian surface with a surface resolution of 1 kilometer.[9]

Images from Mariner 9 revealed surface features far beyond what investigators had expected from the earlier flybys. The earlier spacecraft had by chance photographed the heavily cratered southern hemisphere of the planet, which looks more like the Moon than like Earth. These first closeup images of Mars gave scientists the false impression that Mars was a geologically "dead" planet, in which asteroid impacts provided the primary agent for altering its surface geology. Mariner 9 showed instead that Mars also had huge volcanoes, complex fault zones, and an enormous canyon some 2,800 miles long just south of the equator, named Valles Marineris by the NASA spacecraft team.[10] Detailed examination of numerous channels and valleys suggests that

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[1] The term "planet" derives from the Greek word meaning to wander.

[2] Observations of Mars dominated the scientific interest of Percival Lowell, founder of Lowell Observatory. He popularized the incorrect notion that the surface of Mars was covered with canals, a claim first advanced by Giovanni Virginio Schiaparelli in 1877.

[3] For example, the interplanetary invaders of H.G. Wells' 1897 novel *War of the Worlds* were supposed to have come from Mars. Early in this century, Edgar Rice Burroughs wrote an entire series of adventure novels set on Mars.

[4] See John Noble Wilford, *Mars Beckons* (New York, NY: Knopf, 1990), for a highly readable historical summary of the interest in Mars by Western civilization.

[5] National Research Council, Space Science Board Committee on Planetary and Lunar Exploration, *Strategy for Exploration of the Inner Planets: 1977-1987* (Washington, DC: National Academy of Sciences, 1978), p.43.

[6] The National Aeronautics and Space Act of 1958 was signed by President Dwight D. Eisenhower on July 29, 1958, and became law on Oct. 1, 1958.

[7] Mariners 4, 6, and 7 successfully returned surface images and other data. Mariner 3 failed before reaching the planet.

[8] NASA planned to send two identical spacecraft to Mars, in part to provide redundancy in case one spacecraft failed. Placing the two spacecraft in different orbits would have allowed the two to provide a complete survey of the planet relatively quickly. However, the first spacecraft, Mariner 8, was lost when the Centaur stage on the Atlas-Centaur launch vehicle malfunctioned shortly after liftoff.

[9] This implies that objects equal to or greater than about 1 kilometer diameter could be distinguished on the images. In practice, the ability to resolve surface features also depends on other factors, e.g., the viewing conditions, surface contrast and processing capabilities.

[10] Edward Clinton Ezell and Linda Neumann Ezell, *On Mars: Exploration of the Red Planet 1958-1978* (Washington, DC: National Aeronautics and Space Administration, 1984), pp. 288-297.

Box 5-A — Findings of Mariner 9

Mariner 9 reached Mars in late 1971 and became the first spacecraft to orbit Mars. During the first several weeks of its orbital stay, Mariner 9 encountered a dust storm that completely obscured the surface. Over time, however, the spacecraft provided a complete record of the surface features on Mars at resolutions of 1 to 3 kilometers, which allowed NASA and the U.S. Geological Survey to compile a topographic map of the planet. About 2 percent of the surface in specific areas was imaged at 100- to 300-meters resolution. Mariner 9 discovered massive volcanic mountains, deep channels that reveal evidence of fluid flow in the distant past, and layered sediments in the polar regions. Mariner 9 revealed a hemispherical global dichotomy (half the planet has craters dating from the early history of the planet, while the other half has few craters).

Observations of the cloud systems revealed westerly winds in winter and easterly winds in the summer, weather fronts, lee wave clouds, ice fogs, and other atmospheric meteorological phenomena. Mariner 9 observations led to the realization that Mars has experienced both secular and periodic (cyclic) climate changes.

An infrared interferometer spectrometer evaluated the extremely small amount of atmospheric water vapor, and demonstrated that it exhibits strong seasonal variations. The Mariner 9 ultraviolet spectrometer showed that the amount of ozone in the atmosphere, which is found only in the polar regions, varies with the seasons. It is greatest during the winter, when it reaches some 2 percent of the ozone in Earth's atmosphere, and falls to zero in the Mars summer. The virtual lack of ozone allows ultraviolet light to reach the Martian surface and destroy any organic compounds present in the soil.

SOURCE: W.K. Hartmann and O. Rasper, *The Discoveries of Mariner 9*, NASA SP337 (Washington, DC: U.S. Government Printing Office, 1974); Michael C. Malin, Arizona State University, 1991.

flowing water was once common on Mars.[11] Some scientists speculate that before this water disappeared from the surface, it may have made life possible.[12]

The scientific arguments for finding evidence of extinct or existing life on Mars had been noted as early as 1959.[13] However, only after the Mariner 9 images were available did scientists have direct evidence of the past existence of water that might have supported life. This finding lent additional support to those scientists interested in searching for evidence of extinct or present life on Mars and spurred development of life-seeking instruments on the Mars Viking spacecraft that were then in the design stages.

The Viking program launched two spacecraft toward Mars in 1975.[14] They were carried into orbit by two Titan III launch vehicles on August 20, 1975 and September 9, 1975, respectively. After searching the surface with high-resolution cameras to select safe landing sites, the Viking craft landed on the surface in 1976, photographed the surroundings, analyzed the soil, and tested for evidence of life (box 5-B). The test for life on Mars was inconclusive, although nearly all scientists agree that it showed that no living organisms existed at the Viking sites.[15] These tests, however, made the unexpected discovery that Martian soil in the vicinity of Viking landers is highly reactive

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[11] Michael H. Carr, "Mars: A Water-rich Planet," *Icarus*, vol. 68, 1986, pp. 187-216; "Water on Mars," *Nature*, vol. 326, 1987, pp. 30-35.

[12] Christopher P. McKay and Carol R. Stoker, "The Early Environment and Its Evolution on Mars: Implications for Life," *Reviews of Geophysics*, vol. 27, No. 2, 1989, pp. 189214.

[13] See the summary history of the early search for life on Mars in Ezell and Ezell, op. cit., footnote 10, ch. 3.

[14] Orginally planned for launch in 1973, the Viking launches were slipped to 1975 as a result of a severe budget squeeze.

[15] This conclusion is based not only on the biology experiments but other experiments that attempted to detect organic material in the soil. The conclusion that life does not exist at the Viking sites cannot be extended to other sites on the planet where conditions more conducive to life, e.g., hydrothermal vents, might exist.

Box 5-B — Findings From the Viking Mars Landers

NASA sent two Viking spacecraft to Mars in 1975, which reached Mars orbit in 1976 after nearly a year in transit. Upon reaching Mars orbit, the orbiters surveyed the surface at high resolution to select the best landing sites for the Viking 1 and 2 landers. Both landers separated from their parent craft and executed soft landings at different sites in July and September, 1976, respectively. Viking 1 landed at a site on Chryse Planitia at 22.3 North latitude, 48.0 degrees longitude. Viking 2 landed at the same longitude on Utopia Planitia 25.4 degrees North of Viking 1. The orbiters then began to relay visual images and other data from the landers back to Earth. Although both orbiters and landers were expected to complete their missions within a few months, they lasted far beyond their design lifetimes and continued to transmit data to Earth for several years.

The Viking landers took the first closeup photographs of the surface and transmitted panoramic views of the rocky Martian landscape. They also documented the weather throughout their lifetime on the surface, finding that atmospheric temperatures ranged from a low of -120 degrees Celsius (about the freezing temperature of carbon dioxide, the major constituent of Mars' atmosphere) to a high of -14 degrees Celsius. The landers experienced dust storms and measured the daily barometric pressure (about 1 percent of the barometric pressure on Earth).

The Viking orbiters determined that the north polar ice cap, which lasts through the northern summer, is water ice. They also mapped about 97 percent of the surface. They further showed that the climate in the northern and southern hemispheres differs greatly, as a result of the summer dust storms that originate in the south.

Although a search for life on Mars was the primary experiment for the landers, neither found evidence of life or of organic compounds in the soil. Mars appears to be self-sterilizing. At present, the combination of ultraviolet light that saturates the surface, and the extreme dryness of the soil prevent the formation of living organisms

Orbiter 2 ended its mission on July 25, 1978; Orbiter 1 reached the end of its useful life on August 7, 1980. NASA received the last data from Lander 2 on April 11, 1980 and from Lander 1 on November 11, 1982.

SOURCE: G.A. Soffen, "The Viking Project," *Journal of Geophysical Reviews*, vol. 82, pp. 3959-3970; NASA/Jet Propulsion Laboratory Fact Sheet on Viking.

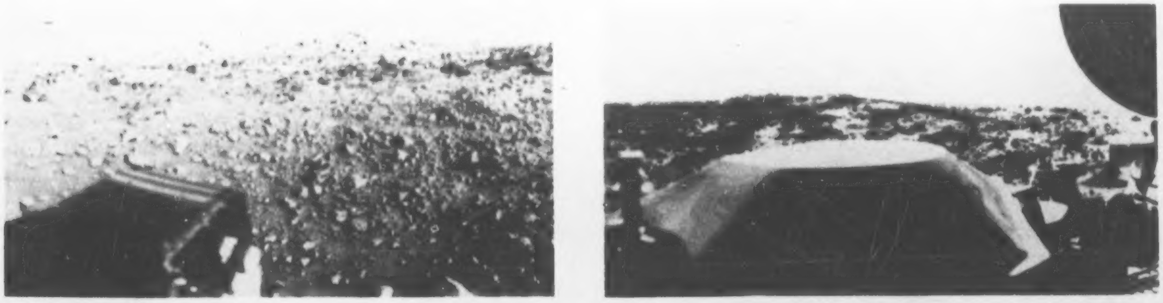

Photo credit: National Aeronautics and Space Administration

First panoramic view by Viking 1 from Mars, showing a rock-strewn surface. The blurred spacecraft component near left center of the left-hand image is the housing for the Viking sample arm, which had not yet been deployed. The spacecraft component in the center of the right-hand image are color charts for lander camera calibration.

chemically, favoring rapid destruction of organic molecules.[16]

Although those who had hoped to find evidence of life on Mars were disappointed in the Viking findings, the evidence of water in an earlier stage of Mars evolution continues to intrigue scientists, both because of what it means for the geological and climatological evolution of Mars, and for evidence concerning the origins of life. In addition, the observations of Mariner 9 and Viking raised a broad variety of questions concerning the formation and evolution of the planet.[17]

Viking I and II were the last U.S. spacecraft to visit Mars. Since the mid-1970s, NASA has pursued investigations of the massive planets beyond Mars[18] and the mapping of Venus by the Magellan spacecraft.[19] These investigations have radically changed our understanding of the surfaces and atmospheres of these planets.

CURRENT SCIENTIFIC OBJECTIVES

Well before the President announced his proposal for human exploration of the Moon and Mars, the scientific community had spent years studying the next steps in the detailed examination of the planets and concluded that because of its proximity and similarity to Earth, Mars should receive special attention. The Committee on Planetary and Lunar Exploration (COMPLEX) of the National Academy of Sciences Space Science Board in 1978 recommended that "the triad of terrestrial planets, Earth, Mars, and Venus, should receive the major focus in exploration of the inner solar system for the next decade. This priority has not changed over time. The ultimate goal in this exploration is to understand the present state and evolution of terrestrial planets with atmospheres. The comparative planetology of these bodies is a key to the understanding of the formation of the Earth, its atmosphere and oceans, and the physical and chemical conditions that lead to the origin and evolution of life."[20] The NASA Advisory Council's Solar System Exploration Committee (SSEC) in 1983 also recommended that a detailed study of Mars should receive priority.[21] These studies led to a proposal for a spacecraft to carry out a detailed study of Mars' atmosphere and surface from a polar orbit.[22] The resulting spacecraft, which is called Mars Observer,[23] is scheduled for launch in September 1992 aboard a Titan III launcher. The SSEC in 1988 reaffirmed the emphasis on Mars by recommending a Mars sample return mission before the end of the century.[24]

The geological, hydrologic, and atmospheric histories of Mars are long, and apparently complicated. Elucidating these scientific stories will require an extended exploration program. Although our current understanding of Mars suggests a number of intriguing questions, future research on the planet, both from orbit and by in situ studies is likely to provide many surprises and lead to whole new lines of questioning. Current questions of scientific interest concerning Mars can be summarized under four broad categories:[25]

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[16] Norman H. Horowitz, "The Biological Question of Mars;" and Gilbert V. Levin and Patricia A. Straat, "A Reappraisal of Life on Mars;" in Duke B. Reiber, *The NASA Mars Conference*, vol. 71 in the *American Astronautical Society Science and Technology Series* (San Diego: Univelt, 1988), pp. 177-185; 186-208.

[17] See, for example, the extensive set of issues in Duke B. Reiber, op. cit., footnote 16.

[18] The so-called Grand Tour of the outer planets by the Voyager spacecraft resulted in exciting new findings about the planets Jupiter, Saturn, Uranus, and Neptune, their rings and their moons.

[19] NASA launched Magellan toward Venus on the space shuttle *Atlantis* in May 1989. It arrived at Venus in August 1990. The Magellan spacecraft has returned highly detailed radar images of the cloud-covered Venusian surface using a synthetic aperature radar.

[20] National Research Council, Space Science Board Committee on Planetary and Lunar Exploration, *Strategy for Exploration of the Inner Planets: 1977-1987* (Washington, DC: National Academy of Sciences, 1978), p. 34.

[21] NASA Advisory Council Solar System Exploration Committee, *Planetary Exploration Through Year 2000: Part One: A Core Program* (Washington, DC: National Aeronautics and Space Administration, 1983).

[22] A spacecraft in polar orbit periodically crosses the North and South Poles as the planet rotates beneath. By appropriately matching the spacecraft's optics with its altitude, it is possible to image the entire planet in a specified number of orbits, just as the polar-orbiting meteorological satellites image Earth.

[23] It was originally termed the Mars Geoscience and Climatology Orbiter.

[24] NASA Advisory Council, *Planetary Exploration Through Year 2000: Scientific Rationale* (Washington, DC: U.S. Government Printing Office, 1988), pp. 83-85.

1. *The formation of Mars* — Insights into the formation of Mars will be derived from chemical and physical information revealed by analyzing surface materials and by estimating the thickness of the crust, mantle, and core, and determining their densities. Better understanding of the conditions that existed during the formation of Mars would assist scientists in understanding the formation of the entire inner solar system, including the Moon and Earth. Because many of the data required for understanding the formation *and* the evolution of a planet are the same, and acquired by the same instruments, specific data requirements are discussed in the next paragraphs on the evolution of Mars.

2. *The geologic evolution of Mars* — From its formation to the present, Mars has undergone many changes in its surface structure and composition. Like its sister planets, Venus and Earth (and the Moon), Mars has experienced continuous bombardment by meteoroids, asteroids, and comets. Also, like Venus and Earth, it has had a long and complicated history of volcanic activity. In addition, the surface has been extensively modified by wind and water action. Despite these similarities, Earth and Mars are very different. Clues as to why the two planets evolved so differently will be found in the morphology of the surface, in the composition, lithology, and distribution of the surface materials, and in the structure of the planet's interior.

   Estimates of composition, physical structure, and distribution of surface materials can be acquired by remote sensing from orbit. The morphology of the Martian surface is now known roughly at a resolution of 200 meters. Mars Observer will photograph small areas at a resolution of 2 meters. However, detailed studies of chemical composition, mineralogy, and ages of surface materials would require relatively sophisticated, mobile[26] analytical stations on Mars[27] and the return of samples to Earth. Samples and surface measurements are required to calibrate the orbital remote sensing data. Samples are also required on Earth because many of the crucial measurements, e.g., determination of ages, isotopic ratios, and percentages of trace elements, can be done only in the most sophisticated laboratories here on Earth. Moreover, scientists cannot predict in advance what measurements would be most important. Having samples available on Earth allows scientists to return repeatedly to the samples with different instruments and make appropriate measurements as their understanding evolves.

   Determination of the gravity field and topography, coupled with seismic data, and other types of depth sounding, will allow scientists to determine the internal density of Mars and how it changes with depth and surface position. This is crucial for determining not only the gross structure of the planet, such as the thickness of the crust and how it varies with location, but also local structures such as ice deposits.

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[25] This discussion derived primarily from Mars Science Working Group, *A Strategy for the Scientific Exploration of Mars*, Draft, September 1990.

[26] Or a network of stations.

[27] These instruments would be much more sophisticated than the instruments aboard the Viking spacecraft, particularly in sample acquisition and handling.

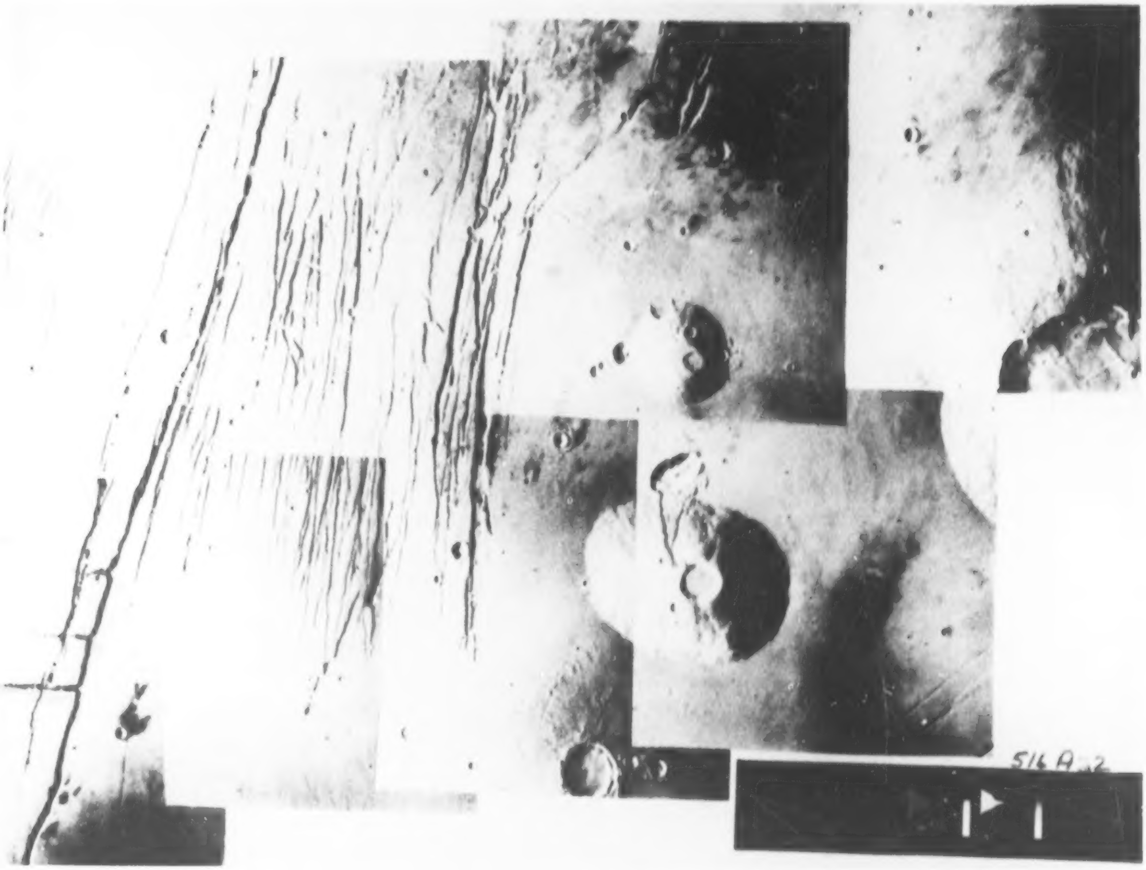

Photo credit: National Aeronautics and Space Administration

Mosaic of pictures from Viking Orbiter 1 shows the northeast margin of the Tharsis Ridge, the youngest volcanic region of Mars. An area of intense crustal faulting can be seen at left, and a cluster of volcanic mountains with prominent summit calderas is visible at right. The volcanoes range from 65 kilometers to 400 kilometers across.

3. *Climate change* — Observations of the Martian surface by Mariner 9 and by the Viking spacecraft, which show numerous channels and dry river valleys apparently caused by water erosion, suggest strongly that the Martian climate has changed radically over time. Liquid water is unstable everywhere on the Martian surface under present climatic conditions. It will either freeze or sublime. Determination of the amount of volatile compounds in the surface[28] soil and rocks would help determine whether the climate did indeed change, or whether another, unknown mechanism is responsible. Spectrometers aboard Mars Observer will provide a global assessment of the inventory of surface volatiles, but detailed studies from the surface would allow scientists to assess whether water in some form[29] might still exist as ice below the surface.

Previous data on the Martian atmosphere has enabled atmospheric scientists to create atmospheric circulation models in order to understand daily and seasonal variations of the atmosphere. Additional seasonal data

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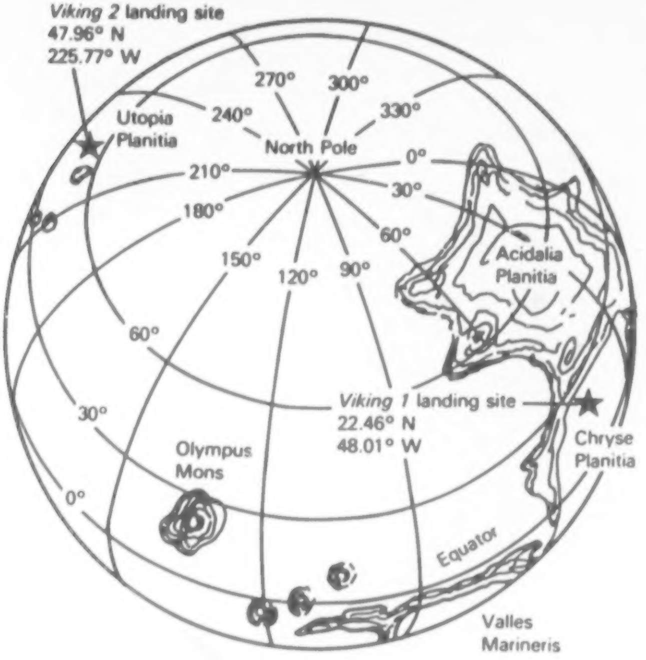
[28] Revealed, e.g., by the amount of ice, hydrated and carbonated minerals, and sulfur, phosphorus, and nitrogen, in the surface soil and rocks.

[29] For example, in the form of ice, or bound in minerals.

Figure 5-1—A View From the Martian North Pole Shows the Location of the Two Viking Sites


Viking 2 landing site
47.96° N
225.77° W
Utopia Planitia
270°
300°
240°
330°
North Pole
0°
210°
30°
180°
60°
150°
120°
90°
Acidalia Planitia
60°
Viking 1 landing site
22.46° N
48.01° W
30°
Chryse Planitia
Olympus Mons
0°
Equator
Valles Marineris

SOURCE National Aeronautics and Space Administration.

acquired both from orbit and on the surface would enable scientists to begin to understand the mechanisms that cause onset of dust storms, and other large-scale atmospheric phenomena.

Scientists have postulated a much thicker atmosphere of carbon dioxide and nitrogen for early Mars. By closely examining sites of early meteoritic bombardment, which may retain important clues about the atmosphere of early Mars, scientists hope to test this hypothesis. High concentrations of carbonates and nitrates in the soil would suggest that the planet held a thicker atmosphere containing carbon dioxide and nitrogen. Carbonates would also confirm evidence of liquid water earlier in Mars' evolution.

4. *Search for life* — The question of whether life existed on Mars at some time in the past has drawn the attention of both scientists and laymen for centuries. Liquid water is essential to life as we know it. The apparent presence of lakes and rivers on Mars at one time implies warmer climates and suggests that conditions necessary to the formation of life might have existed at some time in the past. Did life start and then die out as conditions on the planet changed? The Viking results indicate that life is very unlikely today. Not only was no life detected, but also no organic molecules. Apparently the soil oxidizes and destroys complex organic molecules. However, the prospects for life in the distant past, when water was abundant at the surface, are different. Indeed, past condition on Mars may have been similar to those on Earth when life started here. Biologists conclude, therefore, that the most promising place to look for past life is in ancient sediments that formed when clima-

atic conditions might have been more favorable.[30] Because of the possibility of past life, some scientists hypothesize that life might have survived to the present in specialized niches, e.g., volcanic hydrothermal vents, and that the Viking spacecraft looked in the wrong places.[31] They believe that more definitive life-seeking experiments need to be done before the planet is irretrievably contaminated with terrestrial organisms.

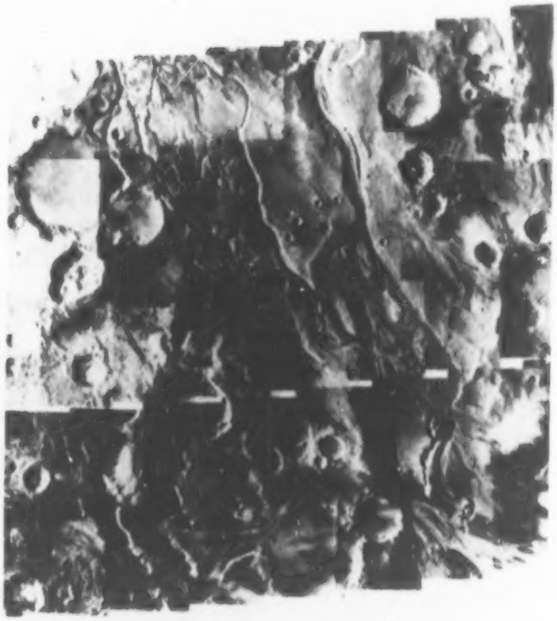


Photo credit: National Aeronautics and Space Administration

This mosaic of the Mangala Vallis region of Mars was taken by Viking Orbiter 1. The central region of the mosaic contains vast channel systems that appear to have been carved by running water in the distant past. Numerous impact craters also appear in the image.

PLANNED AND POTENTIAL ROBOTICS MISSIONS

Scientists have proposed a number of observations of Mars from a distance or missions to the surface in order to collect scientific data on the planet. In addition to identifying new areas of inquiry, data acquired from orbit about Mars would assist in guiding the selection and design of future Mars investigations, including both robotic and human missions. However, only in situ, local measurements can tackle some questions. For example, the investigation of seismic activity, which allows scientists to determine elements of its internal structure and how it changes over time, would require instruments on the planet. Detailed investigations concerning the composition and age of Martian material would require the return of samples for study on Earth. "Thus, the global and in situ studies of the planet and the return of Martian material are complementary components of an overall program of investigation; each of the components is absolutely necessary."[32] A recent examination by the Mars Science Working Group reiterates the importance of this three-pronged approach — global, in situ, and sample return studies.[33] Missions either in preparation or proposed are summarized below:

- *Observations by Hubble* — The wide field and planetary camera on the Hubble Space Telescope is now being used to make long-term observations of Mars from Earth orbit, providing low-resolution, but useful, synoptic data of the atmosphere and surface of Mars throughout the Martian year.[34] Although the wide field and planetary cameras are limited in resolution because of the errors in figuring the Hubble's primary mirror, these data will provide an important baseline for later observations from Mars polar orbit.

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[30] Christopher P. McKay and Carol R. Stoker, "The Early Environment and Its Evolution on Mars: Implications for Life," *Reviews of Geophysics*, vol. 27, No. 2, 1989, pp. 189-214.

[31] R.A. Wharton, Jr., C.P. McKay, R.L. Mancinelli, and G.M. Simmons, Jr., "Early Martian Environments: the Antarctic and Other Terrestrial Analogs," *Advances in Space Research*, vol. 9, 1989, No. 6, pp. (6)147-(6)153.

[32] National Research Council, Space Science Board Committee on Planetary and Lunar Exploration, op. cit., footnote 5, p. 49.

[33] Mars Science Working Group, *A Strategy for the Scientific Exploration of Mars*, Draft, September 1990.

[34] NASA press release, Mar. 18, 1991.

- *Mars Observer* — Mars Observer can be expected to provide data relating to many scientific questions about Mars (box 5-C). After it arrives in the vicinity of Mars in 1993, it will go into a Mars polar orbit, which will allow the Mars Observer Camera (MOC) to image the entire planet.[35] MOC will be capable of viewing locations anywhere on the planet, at resolutions between 300 meters and several kilometers, within any given 24-hour period. It will be able to acquire an image of the entire planet at any resolution between 2 and 7.5 kilometers per picture element in a single 24-hour period, limited only by the data rate returned from the spacecraft. MOC will be able to image the entire planet at a much higher 300 meters per picture element in 7 to 28 days, depending on the data rate.

  MOC is presently scheduled to cover about 0.5 percent of the planet at resolutions between 1.5 and 12.0 meters per picture element, using its high resolution optics. During an extended mission (should one be authorized), it would be possible for the MOC to map the entire planet at 12 meters per picture element in about 600 days, again depending on the possible data rate and the allocation of other spacecraft resources. The ability of an orbiting spacecraft to make observations of deep scientific importance of a planetary surface are exemplified by the results from the Venus Magellan spacecraft[36] and the Viking orbiters.[37]

- *Mars '94* — The Soviet Union currently plans to send an orbiter to Mars in 1994. As it approaches Mars, the orbiter will deploy two small meteorology stations and two dartlike penetrators that will drop to the surface. The orbiters will make a variety of remote sensing observations complementary to those on Mars Observer. The penetrators will analyze the soils and make seismic measurements. In 1996 or later, the Soviet Union plans to send another spacecraft, which will deploy a balloon contributed by France, and a small rover, designed and built by Soviet engineers. The balloon is designed to inflate during the day and float above the planet. At night, cooling temperatures will cause it to drop down to the surface where an attached instrument package can gather surface data.

- *Mars Environmental Survey (MESUR)* — The proposed MESUR mission[38] arises out of an interest in designing a flexible, relatively inexpensive means of providing in situ data on weather, seismic activity, and chemical and physical properties of the Martian soil at various locations on the planet. It would make use of Delta II launch vehicles to send several Martian probes every 2 years, potentially starting in 1998. The probes would be designed as small, spin stabilized, free-flyer spacecraft, based on technology developed primarily for Pioneer Venus and Mars Viking spacecraft. As conceived, four MESUR probes could be launched on each Delta II launch vehicle, and would separate shortly after release from the launch vehicle for the long journey to Mars. When they arrived at Mars, they would use a parachute and airbag to land on the surface, where each would deploy an antenna to communicate with a communications relay orbiter sent separately. It would also be possible to transmit data di-

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[35] The prospect that Mars Observer would still function after a Mars year in orbit is high. Therefore, the spacecraft could be expected to continue to collect data after completing its primary mission. Processing and storing the mass of data from these observations will be a difficult and complex task.

[36] Richard A. Kerr, "Magellan Paints a Portrait of Venus," *Science*, Vol. 251, 1991, pp. 1026-1027.

[37] G. A. Soffen, "The Viking Project," *Journal of Geophysical Reviews*, vol. 82, pp. 3959-3970.

[38] Scott Hubbard and Robert Haberle, *The Mars Environmental Survey (MESUR): Status Report*, NASA Ames Research Center, Feb. 25, 1991.

Box 5-C — Mars Observer

The Mars Observer spacecraft will provide detailed information about the surface of Mars and its atmosphere. Originally termed the Mars Geoscience and Climatology Orbiter, the concept for Mars Observer arose from study of the items of greatest scientific interest on Mars. NASA plans to launch Mars Observer toward Mars in September 1992 aboard a Titan III launch vehicle. It should arrive in August 1993, where it will remain in a "parking orbit" until December, when it is lowered into a circular mapping orbit 380 kilometers above the surface. It will then begin systematic observations of Mars at a variety of surface resolutions. A polar orbit will allow a suite of instruments aboard the spacecraft to collect data over the entire surface of the planet during its planned 687-day (one Martian year) mission lifetime.

Scientific objectives:

- determine elemental composition and mineralogical character of the Martian surface;
- measure the global surface topography;
- measure the gravity field;
- measure the magnetic field and establish its nature; and
- develop a synoptic database of climatological conditions (alterations of atmospheric dust, volatile materials) throughout a seasonal cycle.

Planners expect this mission to provide data that would allow planetary scientists to characterize Mars as it currently exists and create the framework for investigating its past. The data will lead to a better understanding of the geological and climatological history of Mars and the evolution of its interior and surface. It will also give planetary scientists the necessary data for comparing Mars with Venus and Earth.

Mars Observer instrumentation:

Instrument	*Scientific objectives*
Gamma-Ray Spectrometer and Neutron Detector	Determine elemental composition of Mars surface.
Mars Observer Camera (optical wavelengths; 7.5 km, 480 m, and 1.4 m surface resolution)	Obtain daily global synoptic views of Martian clouds and surface; monitor surface and atmospheric features at moderate resolution; examine surface areas of interest at high resolution.
Thermal Emission Spectrometer (Michelson interferometer operating at infrared wavelengths)	Determine and map composition of surface features (minerals, rocks, and ice); study atmospheric dust; measure thermophysical properties of surface; determine atmospheric characteristics.
Pressure Modulator Infrared Radiometer	Map thermal structure of atmosphere in three dimensions over time; map atmospheric dust and condensates; map seasonal variations of atmospheric pressure and vertical distribution of water vapor; monitor polar radiation balance.
Mars Observer Laser Altimeter	Provide a global topographic grid to precision of 30 meters; measure selected areas to precision of 2 meters.

Continued on next page

Box 5-C — Mars Observer—Continued

Instrument	*Scientific objectives*
Spacecraft Radio Subsystem	Use radio system to determine atmospheric properties; characterize small-scale structure of atmosphere and ionosphere; develop a global, high-resolution model of Mars gravitational field; determine both local and broad-scale density-structure and stress state of Martian crust and upper mantle.
Magnetometer and Electron Reflectometer	Establish nature of Mars magnetic field; map Martian crustal remnant field; characterize solar wind/Mars plasma interaction.
Mars Balloon Relay	Use buffer memory of Mars Observer Camera to relay data from Soviet/French balloons expected to be deployed over Mars in late 1995 (Mars '94 spaceprobe).

Operations and Data Analysis

Mars Observer will generate many millions of bytes of data per day. The NASA Deep Space Network will gather the spacecraft data and transmit them to the Jet Propulsion Laboratory (JPL) Space Flight Operations Center in Pasadena, California. However, the various science teams supporting the mission will be located throughout the United States and the world. They will be connected electronically to JPL. Mission data will be stored in a project database.

SOURCE: A.L. Albee and D.F. Palluconi, "Mars Observer's Global Mapping Mission," *Eos*, vol. 71, No. 39, pp. 1099, 1107, Sept. 25, 1990.

rect to Earth at a very slow rate, should communications with a relay orbiter fail.

A network of perhaps 20 instrumented landers would enable two scientific approaches not possible by other means: 1) simultaneous measurements at many widely separated sites for global seismic and meteorological measurements; 2) a variety of measurements at diverse and widely separated surface sites, including surface chemistry and highresolution imaging. The network approach would also allow mission managers to keep the funding profile relatively flat over several years, which has programmatic advantages.

Because instruments would be located at a number of sites, the MESUR experiment as a whole would be less prone to failure. Even if several units failed, the remaining units would still provide useful information. Because it could use existing launch vehicles it would require no new launch system. Because the project would extend over several Martian launch windows, information obtained from the preceding mission could be used to enhance selection of the following study sites. In addition, if funding permitted, the various subsystems could be improved, or altered over time to gather additional data.

- *Rover* — A rover, or collection of small rovers,[39] on the surface of Mars could execute a variety of scientific tasks, from simple observation to sample collection and analysis. Instruments mounted on a rover could, for example, analyze the Martian soil, which might be toxic to humans.[40] Rovers could also be used in characterizing and selecting sites for a possible visit by human crews[41] and, as noted earlier, they could provide support to human crews on the surface.

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[39] See, e.g., David P. Miller, "Mini-Rovers for Mars Exploration," *Proceedings of the Vision-21 Symposium*, Cleveland, OH, April 1990.

With funding from NASA, the Jet Propulsion Laboratory has studied rover technologies for over two decades and has produced a six-wheeled rover,[42] and the Field Robotics Laboratory of Carnegie Mellon University has demonstrated a six-legged "Ambler,"[43] both of which can navigate across rugged terrain semiautonomously. The Massachusetts Institute of Technology Artificial Intelligence Laboratory has explored the use of minirovers for exploration.[44] The design and cost of an actual rover mission would depend on the ability of robotics engineers to improve the rover's ability to navigate autonomously,[45] and reduce the size and weight of rovers to make them capable of being launched on existing launch vehicles and deployed on the surface with existing technology.

- *Sample return* — Scientists who study Mars express a high level of unanimity on the importance of returning samples from the surface of Mars.[46] They note that the samples returned from the Moon have transformed our scientific understanding of the formation of the Moon and its subsequent evolution. Although it is possible to design and develop instruments to carry out limited experiments on the surface of Mars, returning samples to Earth for laboratory analysis is far more productive. First, it is difficult to design robotic in-situ experiments that would be flexible enough to take into account surprises found in Mars surface material.

Returning samples to Earth allows them to be examined by hundreds of investigators using a wide variety of scientific techniques. Samples are a permanent acquisition and can be used over a long period to answer questions that arise as we learn more about the geology of Mars. Radioactive age dating, for example, is of fundamental importance and can only be done in a laboratory with returned samples.

The experience of examining the lunar samples has demonstrated that scientific techniques have improved and evolved over time, allowing investigators to answer questions of the lunar samples that would have been unanswerable 20 years ago. Some powerful techniques, e.g., ion-probe microanalysis, and several mass-spectrometric techniques for determining ages of samples, did not even exist 20 years ago. Mars is much more complicated than the Moon, geologically, and will require more extensive study.

To be most effective in understanding the geology of Mars and the evolution of the planet, a sample return mission would have to gather samples from several locations. It should also gather both surface and subsurface rocks, as the surface soils are suspected to be quite different in composition and chemistry from the rocks.

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[40] The high reactivity of Martian soil might endanger human life if breathed, even though human explorers will be encased in spacesuits. The probability is high, for example, that fine Martian dust could find its way into habitation areas. Hence, its properties should be better understood.

[41] Donna S. Pivirotto, "Site Characterization Rover Missions," presented at the American Institute of Aeronautics and Astronautics Space Programs and Technologies Conference and Exhibit, Huntsville, AL, Sept. 25-27, 1990.

[42] Jet Propulsion Laboratory, *NASA Planetary Rover Program, JPL 1990 Annual Technical Report* (Pasadena, CA: Jet Propulsion Laboratory, Jan. 15, 1991), p. 5.

[43] Eric Krotkov, John Bares, Martial Hebert, Takeo Kanade, Tom Mitchell, Reid Simmons, and William Whittaker, "Ambler: A Legged Planetary Rover," *1990 Annual Research Review*, the Robotics Insitute, Carnegie Mellon University, pp. 11-23, 1991.

[44] C.M. Angle and R.A. Brooks, "Small Planetary Rovers," MIT Artificial Intelligence Laboratory, Cambridge, MA, Apr. 27, 1990.

[45] Autonomy costs more, but is likely to make it possible to operate a rover on the surface of Mars despite communications delays of up to 40 minutes.

[46] James L. Gooding, Michael H. Carr, and Christopher P. McKay, "The Case for Planetary Sample Return Missions: 2. History of Mars," *Eos*, vol. 70, No. 31, Aug. 1, 1989, pp. 745, 754-5; Mars Science Working Group, *A Strategy for the Scientific Exploration of Mars*, Draft, September 1990.

Chapter 6

Automation and Robotics Research and Development

Except for the six Apollo excursions on the Moon, all planetary exploration by the United States and the Soviet Union has been carried out with automated or partially automated systems. However, these spacecraft had only limited capacity to act autonomously,[1] in other words, to evaluate conditions and make decisions on their own; they also had limited capability for teleoperation. Mission controllers programmed them to carry out a specific set of tasks in a specific sequence. As computers have grown smaller and more powerful, automation and robotics (A&R) engineers have increased their capability to design and build semiautonomous mechanical systems capable of performing a wide variety of tasks with minimal direction from mission controllers. A&R experts can now envision, within the next decade or two, the development of both large and small robotics systems capable of traversing a planetary surface, observing the terrain, manipulating and analyzing rock samples, and selecting from the many available samples particular ones to return to Earth for detailed analysis. Such systems would be able to perform a variety of tasks, e.g., construction, equipment installation, and maintenance, telerobotically.

The many engineering disciplines that contribute to A&R are undergoing rapid evolution. If properly managed, they could provide major advances in A&R over the next 30 years, leading to machines capable of assuming a substantially greater share of the human-machine partnership. In the near term, A&R could provide gains in productivity and potential fiscal savings in servicing and maintaining space station *Freedom*.[2] As noted by the Advisory Committee on the Future of the U.S. Space Program, advanced A&R could contribute to the U.S. space program in many areas.[3]

AUTOMATION AND ROBOTICS APPLICATIONS

The basic capabilities involved in space A&R are shared with many other existing or potential A&R applications. For the Moon and Mars, today's A&R research efforts are focused on remotely controlled (teleoperated), and semiautonomous manipulation and mobility. If aggressively pursued, these developments can be expected to provide robots with greater strength, dexterity, and range of motion than humans possess. Improvements in teleoperation, in particular, would extend and enhance human presence in hostile environments.[4] A&R systems of various kinds are most commonly used in manufacturing and in areas hostile to humans e.g., toxic or radioactive cleanup.

The nuclear power industry has made significant use of mobile robots for working in high-radiation environments.[5] The Electric Power Research Institute and the Department of Energy are funding the development of robots for maintenance of nuclear reactors and cleanup of nuclear wastes. Using advanced robot technology in

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[1] U.S. planetary exploration spacecraft have had a small degree of autonomous capability, for example, in the automatic recognition of loss of star lock and procedures for recovering to a 3-axis intertially stabilized mode and pointing the communications antenna toward Earth. The lack of this capability in the Soviet Phobos spacecraft contributed to their failures: Ben Clark, Martin Marietta Corp., personal communication, 1991.

[2] William F. Fisher and Charles R. Price, *Space Station Freedom External Maintenance Task Team, Final Report* (Houston, TX: Lyndon B. Johnson Space Center, July 1990); Mitre Corp., *The Assessment of the Potential for Increased Productivity,*" March 1990.

[3] Advisory Committee on the Future of the U.S. Space Program, *Report of the Advisory Committee on the Future of the U.S. Space Program* (Washington, DC: U.S. Government Printing Office, December 1990), pp. 6 and 31.

[4] Thomas B. Sheridan, "Merging Mind and Machine," *Technology Review*, October 1989, pp. 33-40.

[5] J.T. Lovett and D. Tesar, "Task Requirements for Robotic Maintenance Systems for Nuclear Power Plants," Report to the Department of Energy, University of Texas at Austin, August 1989.

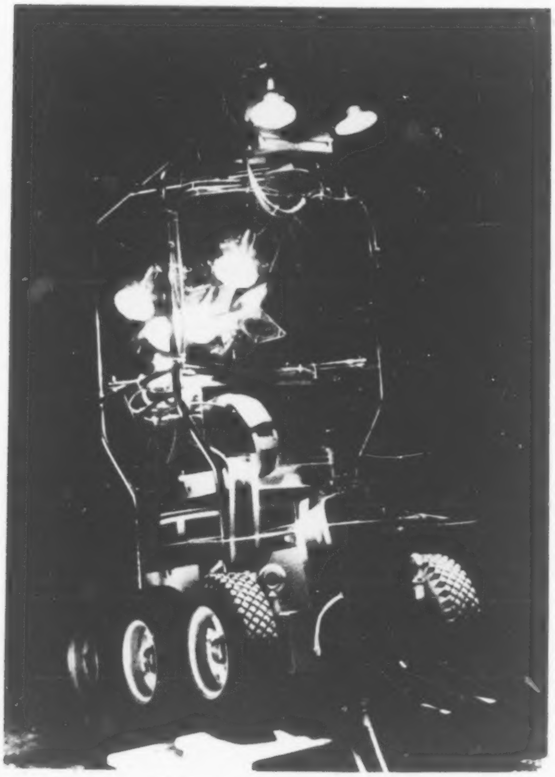

Photo credit. Carnegie Mellon University, Robotics Institute

Teleoperated rover designed for assisting the cleanup of the failed Three Mile Island nuclear powerplant

these environments can drastically reduce occupational radiation exposure, and decrease the forced outages for nuclear powerplants.[6] In the mid-1980s, cleanup of the Three Mile Island powerplant was accomplished with mobile, teleoperated robots equipped with tools for inspection, cutting, drilling, and welding.[7]

In the future, the heavy equipment and service industries can be expected to rely on A&R technologies to carry out dangerous and/or highly repetitive tasks where a high degree of autonomy is required.[8] For example, the mining industry could make use of autonomous vehicles to haul Earth for short distances in open-pit mines, or teleoperated mobile devices to extract minerals in deep shafts. Teleoperated robots are now used for toxic waste cleanup.[9]

The Air Force, Navy, and Army are all investigating the use of A&R technologies for a variety of tasks in hazardous environments, and for repetitive tasks requiring skills in sorting, manipulating, etc. The Defense Advanced Research Projects Agency (DARPA) is supporting basic A&R research for a wide variety of defense applications.[10] A&R technologies can serve important functions for support and for combat.

A recent report by the Air Force Studies Board of the National Research Council examined A&R systems for Air Force primary and support operations. It noted such applications as aircraft servicing, refueling, and assembly; handling munitions; aircraft systems diagnostics; and inspection. It also noted the potential use of A&R systems for a variety of space-related tasks, including spacecraft repair and servicing, and refueling.[11] Figures 6-1 and 6-2 list these technologies and estimate their state of readiness for applications.

The applications of A&R to underwater tasks have many similarities to space applications, especially in the areas of robotic manipulation.[12] In

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[6] Delbert Tesar, College of Engineering, The University of Texas at Austin, personal communication, 1991.

[7] M.D. Pavelek, B.W. McMullen, and K.A. Kreider, "Operational Experiences With Remotely Controlled and Robotic Devices at TMI-2," *Proceedings of the American Nuclear Society Topical Meeting on the TMI-2 Accident: Materials Behavior and Plant Recovery Technology*, Washington, DC, November 1988.

[8] William Whittaker, Robotics Institute, Carnegie Mellon University, personal communication, 1991.

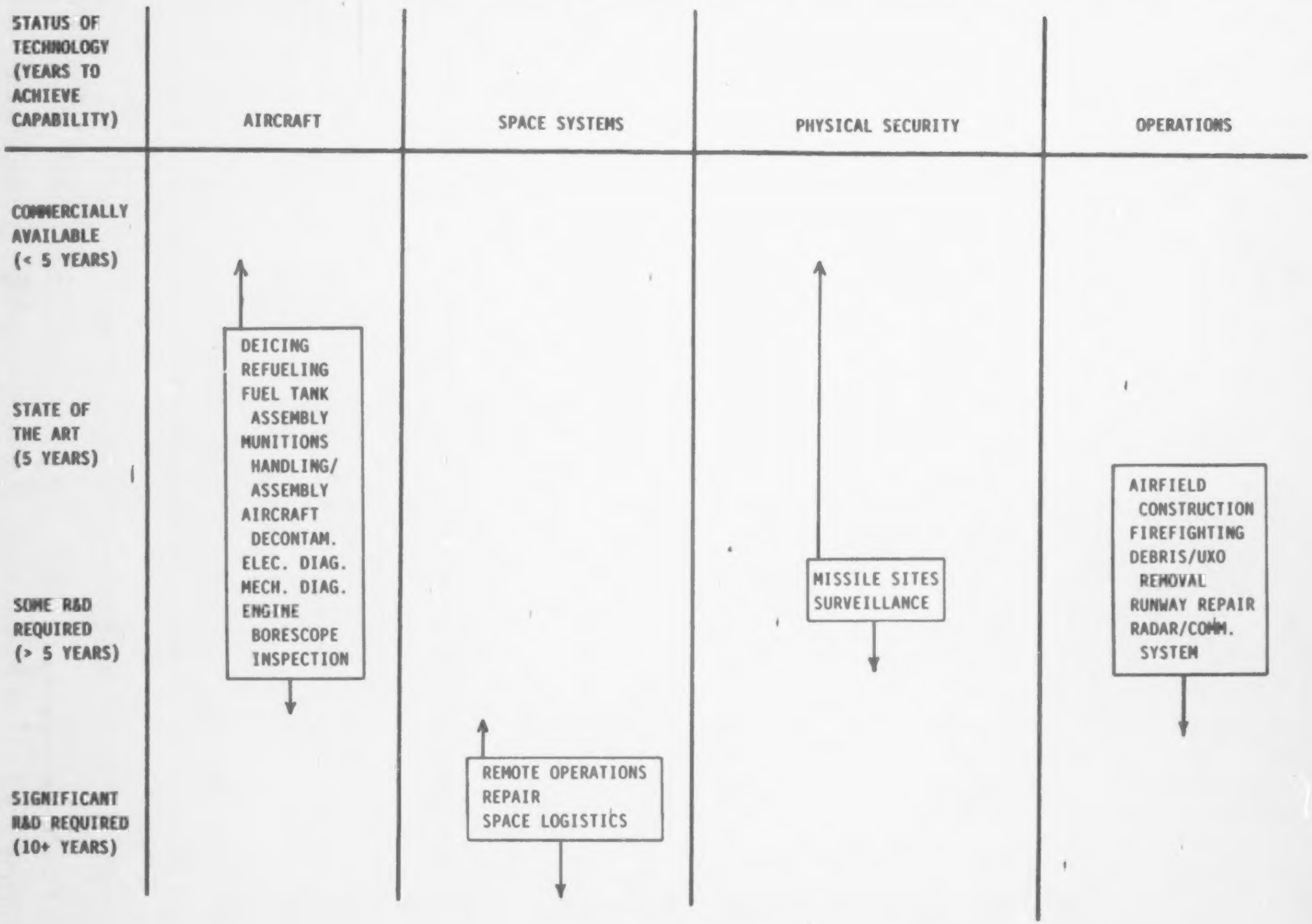
[9] Ibid.

[10] Eric Mettala, The Defense Advanced Research Projects Agency, personal communication, 1991.

[11] National Research Council, Air Force Studies Board, *Advanced Robotics for Air Force Operations* (Washington, DC: National Academy of Sciences, 1989).

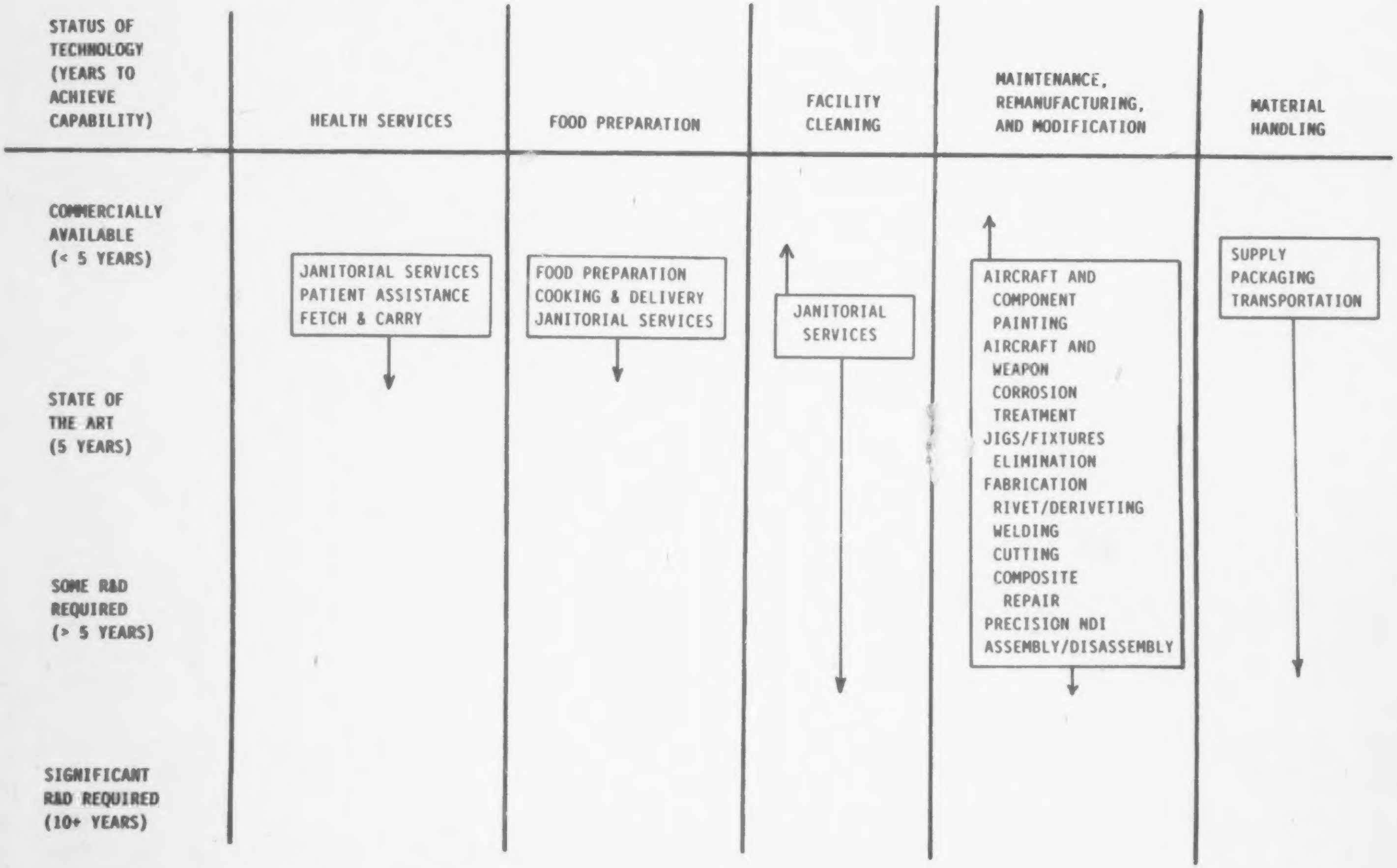
[12] Philip J. Ballou, Graham S. Hawkes, and David Jeffrey, "Tactile, Force and Motion Mechanisms for Manipulator Systems," *Proceedings, ROV'85*, Marine Technology Society, San Diego, CA, 1985, pp. 92-95; Graham S. Hawkes, "Advanced Manipulator Concepts and Applications," *Proceedings, ROV'83*, Marine Technology Society, San Diego, CA, 1983, pp. 72-81.

Figure 6-1—Potential Areas for the Application of Advanced Robotics Primary Operations


STATUS OF TECHNOLOGY (YEARS TO ACHIEVE CAPABILITY)
AIRCRAFT
SPACE SYSTEMS
PHYSICAL SECURITY
OPERATIONS
COMMERCIALLY AVAILABLE (< 5 YEARS)
STATE OF THE ART (5 YEARS)
SOME R&D REQUIRED (> 5 YEARS)
SIGNIFICANT R&D REQUIRED (10+ YEARS)
DEICING
REFUELING
FUEL TANK ASSEMBLY
MUNITIONS HANDLING/ ASSEMBLY
AIRCRAFT DECONTAM.
ELEC. DIAG.
MECH. DIAG.
ENGINE BORESCOPE INSPECTION
REMOTE OPERATIONS
REPAIR
SPACE LOGISTICS
MISSILE SITES
SURVEILLANCE
AIRFIELD CONSTRUCTION
FIREFIGHTING
DEBRIS/UXO REMOVAL
RUNWAY REPAIR
RADAR/COMM. SYSTEM

SOURCE: National Research Council, Air Force Studies Board, *Advanced Robotics for Air Force Operations* (Washington, DC: National Academy of Sciences, 1989).

Figure 6-2—Potential Areas for the Application of Advanced Robotics Support Operations


STATUS OF TECHNOLOGY (YEARS TO ACHIEVE CAPABILITY)
HEALTH SERVICES
FOOD PREPARATION
FACILITY CLEANING
MAINTENANCE, REMANUFACTURING, AND MODIFICATION
MATERIAL HANDLING
COMMERCIALLY AVAILABLE (< 5 YEARS)
STATE OF THE ART (5 YEARS)
SOME R&D REQUIRED (> 5 YEARS)
SIGNIFICANT R&D REQUIRED (10+ YEARS)
JANITORIAL SERVICES
PATIENT ASSISTANCE
FETCH & CARRY
FOOD PREPARATION
COOKING & DELIVERY
JANITORIAL SERVICES
JANITORIAL SERVICES
AIRCRAFT AND COMPONENT PAINTING
AIRCRAFT AND WEAPON CORROSION TREATMENT
JIGS/FIXTURES ELIMINATION
FABRICATION
RIVET/DERIVETING
WELDING
CUTTING
COMPOSITE REPAIR
PRECISION NDI
ASSEMBLY/DISASSEMBLY
SUPPLY
PACKAGING
TRANSPORTATION

SOURCE: National Research Council, Air Force Studies Board, *Advanced Robotics for Air Force Operations* (Washington, DC: National Academy of Sciences, 1989).

conjunction with Deep Ocean Engineering, the National Aeronautics and Space Administration (NASA) Ames Research Center is developing a telepresent underwater system[13] for use in Antarctic research.[14] Earlier use of a remotely operated, underwater vehicle to support research in Lake Hoare, Antarctica was highly effective.[15] Because of these crosscutting applications of A&R technology for underwater, defense, and industrial applications, it will be important to foster supportive relationships in developing technologies for the specific applications.

A&R applications for manufacturing, while important commercially, now only provide a tiny, constrained niche for the development of robotic technologies. The fixed-based manipulators generally used in manufacturing applications can be used in only a narrow range of highly structured tasks. A&R experts face several unsolved problems in extending this technology to unstructured applications. For example, there is no general method for controlling a robot's motions when its hand or tool encounters strong, unpredicted forces or torques in the environment. Today, robot manipulators are still extremely limited when compared to the human hand.

SPACE AUTOMATION AND ROBOTICS TECHNOLOGIES

Robotics in space can assist in a variety of tasks including: exchange of orbital replaceable units; handling of scientific experiments and manufacturing processes; assistance in rendezvous and docking; repair; supply and maintenance of platforms; refueling; and assembly of structures. Until recently, NASA's Flight Telerobotic Servicer (FTS) was being developed for servicing space station *Freedom*.[16] The FTS program provides a testbed for the development and testing of various teleoperated technologies that would extend human capabilities in space. The space shuttle carries the Canadian Remote Manipulator Arm, which astronauts use to perform such manipulative tasks as retrieving and deploying satellites, while they remain inside the shuttle.

The following list of technology elements pertains primarily to space A&R. Each of them have been developed and tested at various levels of readiness for spaceflight. Continued progress in these areas is critical for the development of autonomous spacecraft, planetary rovers, and analytical devices capable of supporting scientific exploration of the Moon and Mars. The robotic exploration of the Moon and Mars will require improvements in technologies that extend perception, cognition, and manipulation in an autonomous mode. Such improvements should materially ehance the human-machine partnership for exploration.

- *Mobility* — Laboratories in NASA and several universities are pursuing both wheeled and legged robotic locomotion. For example, the Jet Propulsion Laboratory (JPL) has constructed a six-wheeled roving vehicle ("Robby") capable of autonomously navigating a path around obstacles from point A on a rugged terrain to a predetermined point B.[17] Under contract to NASA, the Robotics Institute of Carnegie Mellon University (CMU) has designed and built a six-legged, 15-foot-high walking robot called

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[13] Philip J. Ballou, "Report: A Telepresent Underwater Remotely Operated Vehicle System," report to the NASA Ames Research Center (San Leandro, CA: Deep Ocean Engineering, Jan. 22, 1991).

[14] D.T. Andersen, C.P. McKay, R.A. Wharton, and J.D. Rummel, "Testing a Mars Science Outpost in the Antarctic Dry Valleys," *Advances in Space Research*, 1991, in press.

[15] The remotely operated vehicle allowed experimenters to conduct reconnaissance on the bottom of the lake and to plan their research, thus freeing them to concentrate on the most important tasks in the limited amount of time they had underwater (about one-half hour per dive); Steven W. Squyres, David W. Andersen, Susan S. Nedell, and Robert A. Wharton, Jr., "Lake Hoare, Antarctica: Sedimentation Through a Thick Perennial Ice Cover," *Sedimentology*, in press.

[16] In early 1991, the FTS was downgraded to a technology demonstration project within the Office of Aeronautics, Exploration and Technology. Its future is uncertain, but FTS will no longer support space station operations and maintenance.

[17] Jet Propulsion Laboratory, *NASA Planetary Rover Program*, JPL 1990 Annual Technical Report, Jan. 15, 1991.

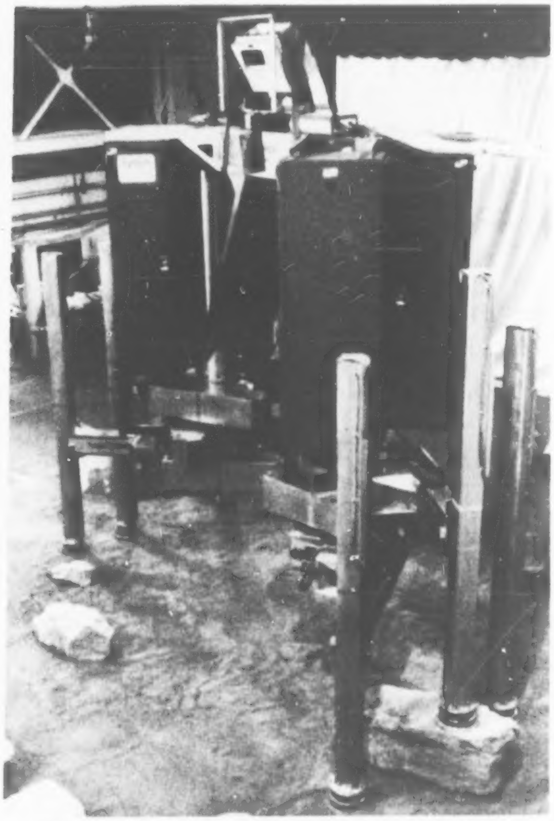

Photo credit: Carnegie Mellon University, Robotics Institute

Six-legged *Ambler* developed by the Robotics Institute at Carnegie Mellon University, under contract to NASA. *Ambler* varies between 4 and 6 meters high and can accommodate a variety of scientific and sampling tools and equipment. *Ambler* can navigate across rugged terrain and climb 30 degree slopes.

the Ambler. The Ambler combines perception, planning, and real-time motion control, and is capable of navigating boulder-strewn terrain.[18]

Researchers at the Massachusetts Institute of Technology (MIT) have concentrated on developing microrovers that employ six legs to "crawl" across the landscape like insects.[19] They represent a radical departure from the larger rovers, both in their size and their modes of navigation (see *Technology Issues,* below).

Researchers have demonstrated all three types of mobile robots in the laboratory and under field conditions. However, they need considerably more experimentation and testing before mission designers can determine which avenue would be most fruitful for planetary exploration. Other approaches to mobility on Mars have been considered as well, including airplanes, balloons,[20] and small, suborbital rockets.

Mobility in space will be equally important in many missions. Staging and executing a mission to Mars, for example, would require assembling independently launched subsystems on orbit. Researchers at Stanford University have concentrated on experimental development of new concepts for freeflying robots in a weightless environment, having fully cooperating arms capable of deft manipulation, either gas-jet or push-off body motion control, and the capability to respond to commands to "fetch, carry and attach."[21]

- *Manipulative dexterity and tactile sensors* — Robotic manipulation systems will eventually be capable of dextrous manipulation far beyond human capability: very long arms could have a pair of short arms at their ends, which in turn may have still smaller arms, agile wrists, and finally, hands with fingers. Such a system is essential in space. Stanford researchers have pioneered the experimental development of well-controlled, long, very flexible arms that carry very quick mini-manipulators at their end capable of performing delicate force-controlled tasks with high precision and agility.[22] Robotics engineers in several laboratories have built various kinds of tactile sensors and manipulators of three and four fingers. JPL and CMU engineers have coupled them with automated vision systems capable of recognizing and selecting among pebbles in a heap. They have also begun to develop specialized automated tools for handling and examining geological specimens.[23]

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[18] Eric Krotkov, John Bares, Martial Hebert, Takeo Kanade, Tom Mitchell, Reid Simmons, and Red Whittaker, "Ambler: A Legged Planetary Rover," *1990 Annual Research Review*, Robotics Insitute, Carnegie Mellon University, 1991, pp. 11-23.

[19] David H. Freedman, "Invasion of the Insect Robots," *Discover,* March 1991, pp. 42-50.

[20] The Soviet Union and France hope to deploy a balloon on Mars later this decade to provide mobility for a package of sensors.

[21] Marc Ullman and Robert H. Cannon, Jr., "Experiments in Global Navigation and Control of a Free-Flying Space Robot." In *The Proceedings of the Winter ASME Meeting*, San Francisco, CA, December 1989.

- *Navigation and path planning* — The development of autonomous navigation and path planning has proved much more difficult than investigators had first expected two decades ago. The decisions humans take for granted when driving a vehicle along a highway or on a rough dirt road involve sophisticated perceptive and cognitive processes that take years to develop. Vehicles that navigate autonomously must be able to recognize a path, guide the vehicle, avoid stationary and moving obstacles, maintain a safe speed, and respond to emergencies.

  In 1990, at JPL, the six-wheeled experimental vehicle Robby has demonstrated, using onboard power and machine vision and computation,[24] its capability to traverse rugged natural terrain at very low speeds. In 1991, Robby demonstrated semiautonomous speeds of 80 meters per hour. Future development will focus on increasing Robby's speed to 2 to 3 kilometers per day.

  Using a neural network controller, researchers at the Robotics Institute at CMU have achieved the ability to "teach" a vehicle to drive autonomously along a highway, gravel, and dirt roads, and even paths at speeds of 20 to 40 miles per hour.[25] Vehicle speeds are currently limited by computing speed and available computing algorithms. Much faster speeds can be expected in the future as computers increase in capability and researchers develop new methods of navigating obstacles. Although automated vehicles, using artificial intelligence methods for cognition, now provide some capability for exploration, goal seeking, and obstacle avoidance, they are still in the research stage, and have relatively limited capabilities. In particular, they have difficulty responding appropriately to situations unforeseen by their designers.

  JPL has shown that it is now possible in the laboratory to plan a path of activity by decomposing it into its component tasks and to predetermine the path of a robot arm to avoid obstacles and reach a preassigned goal or object.

- *Internal representation* — When communications delays become longer than a few minutes, mission controllers experience severe limitations in their ability to control an instrument on a distant body, particularly if the instrument is roving the surface. Hence, if the robot has the capability to form an internal representation of its own location and status, and of updating the representation with sensory inputs, it can operate on its own for a significant portion of the time. Additional commands can then be sent to the robot several times a day, if necessary. Such supervised autonomy may be the only way of controlling a robot on the surface of Mars from Earth.

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[22] E. Schmitz and R.H. Cannon, "Initial Experiments on the End-Point Control of a Flexible One Link Robot," *International Journal of Robotics Research*, vol. 3, No. 3, Fall 1984; Wen-Wei Chiang, Raymond Kraft, and Robert H. Cannon, Jr., "Design and Experimental Demonstration of Rapid, Precise End-Point Control of a Wrist Carried by a Very Flexible Manipulator," *The International Journal of Robotics Research*, vol. 10, No. 1, February 1991, pp. 30-40.

[23] Jet Propulsion Laboratory, *1990 Highlights JPL Automation and Robotics*, January 1991; T. Choi, H. Delingette, M. DeLouis, Y. Hsin, M. Hebert, and K. Ikeuchi, "A Perception and Manipulation System for Collecting Rock Samples," *Proc. of the NASA Symposium on Space Operations, Applications, and Research*, Albuquerque, NM, June 1990.

[24] Erann Gat, Marc G. Slack, David P. Miller, and R. James Firby, "Path Planning and Execution Monitoring for a Planetary Rover," *Proceedings of the IEEE Robotics and Automation Conference*, Cincinnati, OH, May 1990, pp. 20-25.

[25] Dean A. Pomerleau, "Efficient Training of Artificial Neural Networks for Autonomous Navigation," *Neural Computation*, vol. 3, No. 1, Terrence Sejnowski (ed.), 1991.

- *Vision and perception sensors* — Passive stereo vision and active microwave, infrared, or laser rangefinders have both been tested in the laboratory. The rangefinders tend to have larger power requirements than passive stereo vision and need to be qualified for use on the Martian surface. However, they require less computing power and provide more reliable three-dimensional information. Other perception sensors, e.g., those that could test the load-bearing capability of the soil, are in the very early stages of development.
- *Operator interface and mission operation* — The successful completion of a robotic mission will depend in large part on the development of intelligent software and other systems to enable mission controllers to interact with distant robots, having increasing autonomous capability. Engineers at Stanford University have developed an intuitive graphical interface that allows the operator to indicate the desired robotic movement and connection of objects. The tasks are then executed autonomously by a pair of cooperating robot arms. The system at Stanford has been operated from Washington, DC.[26] Equally important areas of research include the development of techniques to provide the operator with a sense of "virtual reality," executive and system simulation software, and force and torque reflection.
- *Automated noncontact instruments* — Both human and robotic missions could make use of these technologies, which include spectrometers, imaging spectrometers, elementary particle detectors, radars, and microwave detectors. Although these are well developed for remote sensing from orbit, they should be adapted for use in close range. JPL has demonstrated software for efficiently processing data in real time. This software would permit the robot to execute conditional commands, e.g., search commands, that depend on ongoing exploration.
- *Computers* — Experiments at JPL and other laboratories indicate the need for onboard, space-qualified computers capable of executing tens of millions of instructions per second (MIPS) to operate large rovers that navigate autonomously. An additional 50 to 100 MIPS-equivalent would be needed for specialized vision processors. Robotics will benefit substantially from advances in computers developed for other uses.

TECHNOLOGY ISSUES

The application of A&R research to the exploration of the Moon and Mars, as well as to industrial, defense, and other applications will require legislative, oversight, and appropriations attention to several crucial technology issues:

- *Interdisciplinary concerns* — A&R draws on a large number of other, rapidly changing engineering disciplines. Robotics traditionally relies on knowledge in such disciplines as mathematics, materials science, dynamics, electromechanical energy conversion, control theory and control engineering, computer engineering, sensor technology, industrial and operations engineering. It draws increasingly on advances in artificial intelligence technology, real-time computing systems and programming methods, simulation technology, and computer networking methods and technology. Despite some significant improvements in A&R as a result of these interactions, artificial intelligence and robotics are generally treated as separate disciplines rather than as one overall discipline that focuses on the development of intelligent systems to define and carry out a variety of well-defined tasks.

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[26] Stanley A. Schneider and Robert H. Cannon, Jr., "Experimental Object-Level Strategic Control with Cooperating Manipulators." In *The Proceedings of the ASME Winter Annual Meeting*, San Francisco, CA, December 1989.

Robotics for exploring the Moon and Mars requires advances in the three broad areas of machine perception, cognition, and action, which in the past have developed in relative isolation. For example, machine perception, which requires a variety of sensors, has evolved from applications such as photo interpretation and manufacturing part recognition, which involve the sensing of still images. These applications, which involve only minimal time constraints, therefore require comparatively simple technology. Machine cognition has evolved as artificial intelligence technology, applied to purely cognitive tasks that are also not constrained by time. Machine action has evolved in robotics and control technologies, usually coupled with simple sensor technology (as opposed to complex perception, which would require sensing and cognition in real time).

The addition of a requirement that robotic devices operate in real time adds a significant constraint into the development of these technologies. Because these areas have evolved relatively independently, A&R experts have relatively little experience with integrating techniques, methods, and hardware developed in each area into an intelligent, functioning whole.[27]

- *Systems integration* — Because robots are complex systems that integrate perception, cognition, manipulation, control, human interaction, and must accommodate system architecture, error detection and recovery mechanisms, and mission planning, systems integration techniques assume a crucial role in making them function effectively. At present, the absence of systematic techniques for creating complete robot archetypes in which the characteristics of interacting subsystems can be fully accommodated is a barrier to actualizing robots of the future. In addition, the design, manufacture, and operation of individual components has not reached a high level of maturity.

The scale of the problem faced by robotics engineers can be seen in an analogy to an automobile.[28] Automobile systems have matured over many years. The brakes, electrical systems, transmissions, and so forth are well understood. Furthermore, the transmission system interacts little or not at all with the brakes. Hence, improvements in the braking system can be pursued with little regard for its possible affects on the transmission system. In most robotic systems, however, even small changes in one subsystem, e.g., an acuator, may require changes in another subsystem.

Operation of the automobile provides another insight into the difficulty of crafting systems integration techniques. A human driver must constantly monitor the vehicle, sensing internal and external conditions, controlling the automobile in real time despite uncertainty concerning what lies around the next bend, and correcting control errors along the way. A robotic operator must do the same. The robotic system must cope with uncertainty in control (sensors never report exactly the state of nature) and with uncertainty in control (the robotic mechanism never performs exactly the issued command). Each of the subsystems must tolerate errors and mistakes committed by other subsystems. Furthermore, it must do so in real time, because the automobile is moving. Given the current state of robotics technology, all contingencies for robotics systems must be anticipated and accounted for by designer beforehand.

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[27] Such integration is beginning, e.g., at Stanford University, where teams in aerospace robotic control and in artificial intelligence are working closely together to solve problems of mutual interest.

[28] Eric Krotkov, Robotics Institute, Carnegie Mellon University, personal communication, May 1991.

Existing robots have little capability for responding to unforeseen circumstances and for learning from experience.

- *The role of artificial intelligence* — Intelligent systems (artificial, or machine intelligence) should play a major role in the development of robots. If properly implemented in a system architecture, intelligent systems provide the user with the capability to "use, modify, create, and exploit models" of which they are a part.[29] They provide the "brains" of a robotic device that ideally allows it to approach a problem with flexibility.

  Areas of artificial intelligence and control engineering that can assist the development of effective A&R devices (table 6-1) include: human/machine interfaces; overall systems architecture, including the computational environment, languages, operating systems, and network interfaces; verification and validation of critical technology elements, e.g., software and processing elements; and the capability for evolutionary growth of the system architecture.

- *Technology strategies* — The current intellectual ferment in A&R technologies may offer opportunities for organizing missions in novel ways. For example, until recently, most scientists assumed that a Mars rover would be a relatively large vehicle (hundreds of kilograms) that would require a large amount of computing capacity to traverse the Martian surface. Although such a rover could carry a number of tools and use part of its computing power for scientific analysis, because it would be required to do so many tasks, NASA could probably provide funding for only one or two such rovers. Scientists would therefore suffer the risk that a failure in one or more major subsystems would destroy most or all of the mission. In addition, although a single rover might traverse many tens of kilometers, it would be unlikely to be able to explore a relatively small region of geographical interest.

Table 6-1 — Technological Challenges for Intelligent Systems

- Improvements in multiple sensor integration, processing, and understanding.
- Development of distributed knowledge-based systems that can cooperate with each other in real-time distributed operational environment.
- Improvements in systems architecture and integration including the development of intelligent user interfaces, real-time fault management, and a high-performance, real-time computational environment.
- Improvements in systems verification and validation.
- Development of focused testbed and flight demonstrations.

SOURCE: The National Aeronautics and Space Administration, Ames Research Center, 1991

In the last few years, A&R researchers have experimented with small rovers[30] and have suggested that sending many of these would increase the chances of acquiring significant scientific data. Several micro- or minirovers could be transported on existing launch vehicles to different locations, making possible broad coverage of the planet. Some researchers have expressed concern that small rovers would be unable to carry enough computing power to store or generate a map of their location in order to navigate safely among obstacles. However, if the small rover were given the capacity to move across the landscape without an internal map, the necessary computing capacity would decrease dramatically. Researchers at MIT have built legged small rovers based on so-called subsumption architecture, which requires no prior instructions about how to navigate.[31] These rovers are given only a set of rules about the order in which to move their "legs." Hence, they act more

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[29] Eberhard Rechtin, *Systems Architecting: Creating and Building Complex Systems* (New York, NY: Prentice Hall, 1991), p. 100.

[30] David P. Miller, "Mini-Rovers for Mars Exploration," *Proceedings of the Vision-21 Symposium*, Cleveland, OH, April 1990.

[31] David H. Freedman, "Invasion of the Insect Robots," *Discover*, March 1991, pp. 42-50.

Photo credit: California Institute of Technology, Jet Propulsion Laboratory

Experimental minirover, named *Tooth*, developed by the Jet Propulsion Laboratory. Tooth is capable of carrying out a limited number of tasks, operating either under command or autonomously.

like insects than higher level animals, making their way across the landscape by trial and error rather than by carrying an internal map and making decisions about which way to move. Provided with appropriate optics and sensors, they can nevertheless traverse the landscape.

Many A&R experts argue with this approach, pointing out that to do useful work on the planet, rovers would need internal guidance, which would require considerable computing capacity, unless they were operated from Earth remotely.[32] They would also have to carry adequate electrical power and instrumentation (optics and electronics), which would be difficult or impossible in mini- or microrovers. Even carrying adequate vision and telemetry systems might severely strain the capacity of small rovers. As computers grow smaller and smaller and A&R engineers learn how to build smaller and lighter mechanical systems, they may be able to build rovers with sufficient computing capacity to do useful planetary reconnaissance and analysis in several regions.[33] Providing adequate electrical power to small rovers will prove a challenge, because existing batteries can carry only a limited amount of power compared to their weight and size, and solar power requires both storage batteries and a relatively large solar panel. A Radioisotopic Thermoelectric Generator (RTG), which could be used on a large rover, would be too heavy and bulky for a small one.

- *Communications delays* — Communications delays between the Earth and Moon (3 seconds) and between Earth and Mars (6 to 40 minutes) would introduce significant complications to the operation of robotic devices on the Moon or Mars directly from Earth. Research has shown that delays of the order of seconds can be accommodated by using a combination of machine vision and modeling of the environment in real time.[34] Hence, it appears likely that A&R engineers will learn how to overcome the time delays associated with the teleoperation of a rover on the Moon and having it carry out a complex set of tasks.[35]

The time delays inherent in communicating with Mars will require building much more autonomy into rovers or other robotic devices, or require considerably more patience and reduced scientific expectations. For example, after assessing the surround-

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[32] Here again, the delay times could make such research agonizingly slow.

[33] As suggested in the last chapter, this may be an area for fruitful international collaboration, as the Soviet Union, the European Space Agency, and Japan are all considering employing rovers to explore the Moon and Mars.

[34] Lynn Conway, Richard A. Volz, and Michael W. Walker, "Teleautonomous Systems: Projecting and Coordinating Intelligent Action at a Distance," *IEEE Transactions on Robotics and Automation*, vol. 6, No. 2, April 1990, pp. 146-158.

[35] Soviet engineers demonstrated the possibility of accomplishing relatively simple teleoperation tasks in the mid-1970s when they drove the Lunakhod rover many kilometers across the lunar surface.

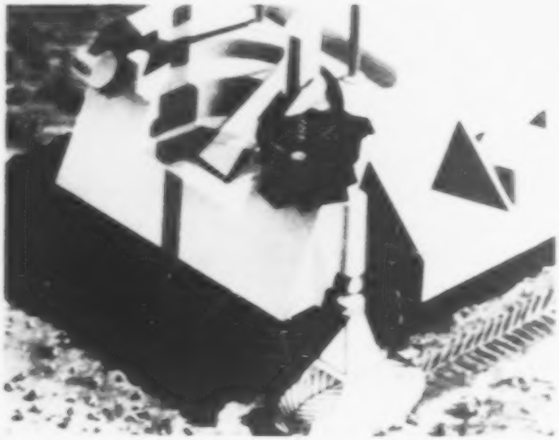

Photo credit: National Aeronautics and Space Administration

Artist's conception of a core sample (center) undergoing analysis after being obtained from the planetary surface by coring bit (shaded device left of center)

ings of a Mars rover, the human geologist on Earth could direct the rover to move around or over large and small obstacles to a specified location in the landscape, pick up a rock sample, examine it in several wavelengths, send the resulting data back to Earth, and wait for further instructions. These actions require the robot to be much more autonomous than existing ones. After the robot has accomplished that set of tasks, the geologist would be in a position to determine whether the sample should be retained for further examination or discarded. If the geologist decides to retain the sample, he or she might instruct the robot to analyze it further, or place the sample in a bin for eventual return to Earth. The scientist and the rover could then repeat their close collaboration in another promising geographical area. In this way, the distance between Earth and Mars would only slow up, not seriously impede, the robotic exploration of Mars.

- *Flexibility and resilience* — Flexibility and the ability to adapt to new situations are two qualities often cited as characteristic of human exploration. Robotic spacecraft also share these characteristics to some extent and have demonstrated the ability to tolerate some software and hardware deficiencies. For example, in the late 1970s, software engineers were able to work around a potentially crippling loss of one of the receivers and the failure of the frequency lock circuit on the other aboard the Voyager spacecraft. Because it was possible to reprogram the tiny memory (only 4 kilobytes) within Voyager, it went on to return startling images of the outer planets and their moons.[36] More recently, the Magellan spacecraft, which is generating a detailed radar map of the surface of Venus, began to spin slowly out of control.[37] With the help of ground controllers who developed means of working around the problems, the spacecraft was able to recover and continues to send crisp radar images to Earthbound scientists.[38]

The fact that ground controllers have been able to overcome such difficulties results in part from good spacecraft design, which incorporates redundancies and multiple paths for decisionmaking, but also from clever and insightful manipulation of the spacecraft's software. By building in more sophisticated fault-tolerant capability and self-healing processes, in both hardware and software, future spacecraft can be made even more flexible and may require less oversight from controllers on Earth.

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[36] Giulio Varsi, "Advances in Space Robotics," IAF-89-032, Presented at the 40th Congress of the International Astronautical Federation, Malaga, Spain, Oct. 7-13, 1989. Varsi also points out that, "Reprogrammability has made it possible to improve the precision of the spacecraft trajectory, as more information on the ephemeris of planets and satellites was acquired during the mission and to enhance the performance of the instruments by developing on the ground and then transmitting to the onboard computer better algorithms for image coding and for motion compensation of the scan platform."

[37] Michael A. Dornheim, "Magellan Radar Produces Sharp Images, but Computer Problems Vex Controllers," *Aviation Week and Space Technology*, Aug. 27, 1990, p. 29.

[38] Richard A. Kerr, "Magellan Paints a Portrait of Venus," *Science*, vol. 251, 1991, pp. 1026-1027.

Tomorrow's challenge is to design and build an equivalent level of flexibility, resilience, and fault tolerance[39] in machines that will experience direct mechanical contact with the environment. With few exceptions,[40] most spacecraft have had to deal only with celestial mechanics and long-range gravitational forces. The precise positioning and motion of the spacecraft platform has occurred in free space, with no mechanical contact with the surface.

FUTURE PROSPECTS FOR A&R RESEARCH AND DEVELOPMENT

Resolving these issues will require basic technology development and testing at both the subsystem and system level. It will also require consistent funding. One of the most important concerns expressed to OTA staff by project managers both within NASA and externally was the inconsistent pattern of funding for robotics programs.[41] Programs would be started, begin to provide useful results, and then be canceled abruptly. Although technology research programs may commonly experience a certain lack of stability as research priorities change, sometimes abruptly, the United States is unlikely to see major progress in the development of A&R technologies until they are taken much more seriously.

The United States has the capability and the resources to implement a highly competitive A&R program. However, it presently lacks the structure to carry one out. An integrated A&R program to serve government needs could engage the capabilities of the universities, government laboratories, and industry. For example, universities could efficiently conduct basic research and then, in cooperation with the appropriate government laboratories, participate in further refinement and demonstration of technology feasibility and readiness. Promising technologies could then be handed over to development centers and aerospace industries for final development, validation, and implementation. If A&R programs in government laboratories and industry were more tightly coupled, A&R technologies would have a higher chance of finding their way into industrial applications and commercial ventures.[42]

In some respects, A&R technologies were oversold in the 1980s because the technology seemed more simple, tractable, and mature than it was. Continued technology development, and experience with successful systems, could raise public awareness of the utility of A&R systems and create a setting in which A&R engineers can be more innovative in applying them to space and Earthbound applications. There are many possible blendings of perception, cognition, and action at a distance. For example, we might employ teleautonomous systems that can operate autonomously most of the time, but easily be brought under teleoperated control when necessary. Greater understanding of both the promise and limits of A&R technologies would assist development of such systems. Tying the development of new robotic technologies to specific planetary projects, such as emplacing scientific instrument packages on the Moon, or exploring the surface of Mars, should help focus the development of new technologies.

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[39] Robotics engineers find continuing challenge in providing fault tolerance for mechanical structures that is equivalent to the fault tolerance now being incorporated in computer software.

[40] For example, Viking spacecraft on Mars, and the Lunakhod rover on the Moon.

[41] Although inconsistent funding may not be unique to NASA's A&R program, it has hampered efforts within NASA to exploit the capabilities of A&R technologies.

[42] At present, the aerospace industry is not closely coupled to other industries. Hence, effective technology transfer to the broader manufacturing and service industries will require sustained effort.

Chapter 7

Costs of the Mission From Planet Earth

As a proposed new program with significant long-term costs, the Space Exploration Initiative (SEI), or Mission from Planet Earth, will come under careful scrutiny by Congress. Estimates by the National Aeronautics and Space Administration (NASA) and the aerospace industry suggest that the total expenditure over a 30- or 35-year period for establishing a lunar base and mounting a crewed Mars mission, including robotics missions, could reach a range of $300[1] to $550 billion[2] (1991 dollars), which would make it the most costly program in NASA's history.[3]

However, at this early stage in the long process of planning the components of a Mission from Planet Earth, which could include a variety of optional paths,[4] any estimates of costs are necessarily extremely uncertain. As the Committee on Human Exploration of Space of the National Research Council pointed out, they "are likely to remain so for some time."[5] Costs depend critically on the range and scale of planned activities, their schedule, and on a multitude of other factors—some well known, some only dimly perceived, and some as yet totally unrecognized. The ability to predict costs will therefore depend heavily on new information developed in the course of the program. Cost estimates also depend on the projected costs of developing new technologies and manufacturing the systems critical to the success of the various projects within the overall plan.

At this early stage of planning for a Mission from Planet Earth, when the many program options available are still under discussion,[6] few of the systems have been defined well enough to estimate costs, even loosely. The models used to estimate costs are notoriously unreliable in projecting the costs of systems incorporating new technologies because the models depend on past development experience. The more familiar designers are with the technology, the more accurate are the cost estimates.[7] For example, NASA and the Department of Energy may wish to pursue development of nuclear energy as the propulsion mode for transporting humans from Earth orbit to Mars, because, if successful, nuclear propulsion could dramatically reduce the transit time between the two planets. Yet the probable costs for developing nuclear propulsion are very poorly known because the development process contains a significant number of unknown costs. The costs of an interplanetary vehicle powered by nuclear propulsion are also poorly known. Detailed design studies could reduce the cost uncertainties, but only marginally, until additional technology development is done.

If, after pursuing development of nuclear propulsion technologies, the total development costs seem too great, NASA might decide instead to use chemical propulsion, which is much better known, to transport people to Mars, even though the journey could take much longer. Yet the costs of an interplanetary vehicle propelled by chemical fuel are also uncertain. Nearly every system in an exploration program faces similar development choices and uncertainties.

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[1] Over 30 years, General Dynamics Space Systems Division, "Lunar/Mars Initiative Program Options – A General Dynamics Perspective," Briefing Report, March 1990.

[2] Unpublished estimates developed by NASA for its study entitled, *Report of the 90-Day Study on Human Exploration of the Moon and Mars* (Washington, DC: NASA, November 1989). This estimate, which was for a 35-year period beginning in 1991, includes a 55-percent reserve, and would fund a permanent lunar base and robust human exploration of Mars.

[3] By comparison, the Apollo program cost about $116 billion in 1991 dollars.

[4] NASA, *Report of the 90-Day Study on Human Exploration of the Moon and Mars* (Washington, DC: NASA, November 1989); Synthesis Group, America at the Threshold (Washington, DC: the White House, June 1991).

[5] National Research Council, Committee on Human Exploration of Space, *Human Exploration of Space: A Review of NASA's 90-Day Study and Alternatives* (Washington, DC: National Academy Press, 1990), p. 31.

[6] See, e.g., Synthesis Group, op. cit., footnote 4.

[7] U.S. Congress, Office of Technology Assessment, *Reducing Launch Operations Costs: New Technologies and Practices*, OTA-TM-ISC-28 (Washington, DC: U.S. Government Printing Office, September 1988), app. A.

Further, in a large project, the development of new technologies is interlinked. New technologies are not "in place" until they are integrated into the rest of the system. Unexpected delays in developing and testing a new launch system, for example, would delay an entire project, even if other technologies were ready. Problems even with supporting technologies and systems may nevertheless delay the project. For example, many payloads designed for launch on the space shuttle had to wait for several years to be launched after the loss of *Challenger*, because to redesign and alter them for launch on expendable launch vehicles would have entailed substantial extra cost.[8] Hence, it is far too early to judge the total costs of exploratory missions to Mars using either robotics spacecraft or human explorers.

As NASA develops alternative plans for a Mission from Planet Earth, it should examine carefully which technologies would lead to lower overall costs (including development, manufacturing, and operational costs). Some technologies, e.g., those for space transportation, could have broad application in the space program, and would therefore contribute to overall development of U.S. efforts in space. Others, e.g., space nuclear power and nuclear propulsion, would assist in a drive to expand the human presence beyond Earth orbit, but would have less application elsewhere.

COST ISSUES

Comparing Robotic and Crew-Carrying Costs

Because of the large uncertainties in making cost estimates for the Mission from Planet Earth, comparisons between a set of robotic missions and human missions are also highly uncertain. However, experience with previous space projects provides some guidance. Several OTA workshop participants estimated that, based on their experience with developing and managing various space projects, specific robotic exploration projects might cost one-tenth to one-hundredth as much as human exploration.

These differences are the result of greater weight for human missions, the need for life-sustaining systems, and the need to provide for crew safety. However, comparisons between the costs of carrying out missions using only robots and the costs of crew-carrying missions can be deceiving because the two kinds of enterprises would often accomplish different objectives.

The overall mission strategy would also have a major effect on the costs of either robotic or crew-carrying missions. For a Mars mission, it would, for example, depend on whether human crews would expect to work and live largely in habitats on the Martian surface while sending robotic rovers out to explore, whether crews would themselves do most of the exploring, or whether they would remain in orbit about the planet controlling rovers on the surface.

It is possible at this stage to reach very limited conclusions about total costs of both robotics and human exploration by examining several major systems that would be required as elements of the overall architecture of a Mission from Planet Earth. Figure 3-1 in Chapter 3 presents technologies in eight categories that may be needed to mount robotics exploratory ventures, develop a permanently occupied lunar base, and send a human crew to Mars. This figure reveals two major conclusions. First, human exploration of the Moon and Mars would necessitate development of some nine new critical technologies, each one of which could cost several billion dollars to develop. For example, the development and testing of a new Earth-to-orbit space transportation system (the National Launch System) could cost about $11 billion (1988 dollars), including facilities.[9] Second, robotics missions would require far fewer expensive new technologies and systems. With the possible exception of aerobraking[10] for a Mars mission,[11] robotics exploration (sample return mission) would require the development of few major new technologies beyond automation and robotics (A&R) technologies, though several listed would clearly increase the chances of successful completion of certain scientific missions, and others would provide considerable leverage in accomplishing some science objectives.

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[8] It cost between $30 and $40 million to reconfigure the Cosmic Background Explorer (COBE) satellite for launch on an expendable launcher after *Challenger* was lost.

In attempting to understand cost comparisons between missions that would use robotic technologies on the Moon or Mars and those that would use crews, Congress could ask NASA to present the costs *and cost uncertainties*[12] as well as the benefits and drawbacks of various alternatives. Congress could then decide whether the estimated costs justified expending tax dollars.

Schedule

Each project carries with it an optimal timetable for completion that results in minimum costs. Trying to push technology and organizations too fast results in higher total costs. Stretching out the schedule or delaying it once started also result in higher costs. Because the risks of incurring higher than optimal costs increases with the size of the project, the Nation might be well advised to break up the Mission from Planet Earth into a series of relatively small projects,[13] each with its own objectives and schedules. Such a strategy should make budgeting easier and reduce the risk that any one project would suffer being delayed, especially given the extremely long timescale for the Mission from Planet Earth. However, under these circumstances, the overall plan would have to be extremely flexible to account for unexpected successes or delays. If everything works out, a fully integrated approach is much less costly than a flexible one. But a flexible approach allows plans to change as budgets and national priorities change over time.

As noted earlier, the OTA workshop concluded that the scientific objectives for exploring the Moon and Mars could be pursued on a wide variety of timetables, depending on the availability of technology and funding, and scientific progress. Launch opportunities for Mars occur about once every 2 years. Launches to the Moon can be carried out several times a month. Hence, scientific missions can be planned and executed as new information indicates new questions to ask. However, political or other objectives may suggest a particular timetable, such as the date of 2019 that the Bush administration has proposed for landing a crew on Mars, which is 50 years after the first Apollo landing. Given a timetable, planners can produce an overall system architecture to fit within it.[14] An architecture based on political considerations may not accomplish the full range of possible scientific objectives, in part because planners experience considerable temptation to cut scientific objectives in order to meet a predetermined schedule, especially when stretching the schedule would result in higher overall costs.

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[9] Manufacturing and operations costs would be at least $70 million per copy (1988 dollars). U.S. Congress, Office of Technology Assessment, *Access to Space: The Future of the U.S. Space Transportation System*, OTA-ISC-415 (Washington, DC: U.S. Government Printing Office, 1990), p. 36.

[10] Aerobraking makes use of the Martian atmosphere to slow down an interplanetary vehicle to the point that it can be captured by Mars' gravitational field. A very massive interplanetary vehicle would either have to use aerobraking or carry sufficient fuel to slow it for capture by Mars.

[11] Figure 3-1 lists aerobraking as a critical technology for returning samples from the surface of Mars. However, the strength of its importance for such a mission depends directly on how the mission is carried out. A robotics rover mission using small rovers would not necessarily need aerobraking. Such a mission could be accomplished with existing technology.

[12] The amount of cost uncertainty provides a measure of the cost risk involved.

[13] Planetary projects, by their nature, tend to be rather large and take several years to plan and complete. Delays in major subsystems or in supporting systems, e.g., space transportation, can introduce substantial delays in such projects. Nevertheless, it may be more cost-effective in the long run for project leaders to resist the temptation to load many different objectives onto a single project.

[14] See, e.g., the system architectures examined in the Synthesis Group, *America at the Threshold* (Washington, DC: The White House, June 1991).

Operational Costs

The operational costs for exploration, whether robotic or human, could be very high. Such costs are notoriously hard to judge, as they depend heavily on the success engineers have in developing systems that require relatively little continuing oversight. For example, when the space shuttle was under development, planners expected operational costs to be high in the initial operational stages, but to decrease steadily as operators gained experience with its many subsystems.[15] Over time, yearly operational costs of the shuttle have actually increased[16] and NASA has been unable to decrease the per-flight operational cost by increasing the flight rate.[17] In part, the wide disparity between expectations and reality in operational costs results from the fact that when budgets became tight as the shuttle was under development, items that would have reduced long-term operational costs, but required near-term development, were often cut from the shuttle budget. The result was a series of near-term reductions at the expense of long-term continuing costs.[18] For systems designed to support humans, safety considerations lead to numerous design improvements *after* a system has been built, which also increases costs.

As planning for the Mission from Planet Earth proceeds, it will be important for planners to examine carefully the operational costs of each project within the overall plan, including robotic ones, and determine whether operational costs can be reduced. By reducing the number of personnel required, A&R technologies could be used to control costs. In the Shuttle program, for example, the large number of contractors and NASA employees required to refurbish and launch each orbiter, and to follow the missions while in progress, is a major contributor to overall mission costs.[19]

Reducing Costs

As noted, costs will also depend on new technologies that might be developed during the prgram. Actual costs could be higher or lower depending on the technological hurdles encountered and the cost reducing effects of technological and management innovations. Many of the A&R technologies being developed to reduce manufacturing costs on aircraft assembly lines, or to reduce the costs of launch vehicles, may have particular utility for the Mission from Planet Earth.[20]

The proposed Mars sample return mission provides an illustrative example. Early studies suggested that the costs of sending spacecraft to Mars to return a sample to Earth might reach about $10 to $15 billion.[21] Yet recent studies suggest that miniaturized robots and simplified objectives might make it possible to mount a more limited sample return mission for much less cost.[22] For example, small robots could be launched on Delta or Atlas launch vehicles, which are available today from commercial launch service companies. Because many small robots could be sent to several different locations and landed using existing technology, they could potentially sample wider regions than a single rover collecting samples from the surface. Even if several small rovers were to fail, the remaining ones would still carry out their missions, reducing overall mission risk compared to a single rover/sample return mission. Yet, small robots may not be able to carry the computing capacity necessary to do intricate tasks,[23] or tasks requiring the use of heavy equipment.

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[15] Advisory Committee on the Futbre of the U.S. Space Program, *Report of the Advisory Committee on the Future of the U.S. Space Program* (Washington, DC: U.S. Government Printing Office, December 1990).

[16] NASA outlays for space shuttle operations have increased about 17 percent per year since 1988. Projected outlays for fiscal year 1991 equal $2.79 billion.

[17] U.S. Congress, Office of Technology Assessment, *Reducing Launch Operations Costs: New Technologies and Practices*, OTA-TM-ISC-28 (Washington, DC: U.S. Government Printing Office, September 1988).

[18] Ibid., pp. 5-6.

[19] Ibid., p. 40.

[20] Ibid., p. 4.

[21] "Mars Rover Sample Return, Technical Review, Final Report, vol. 5," Jet Propulsion Laboratory, Sept. 22, 1988.

[22] David P. Miller, "Mini-Rovers for Mars Exploration," *Proceedings of the Vision-21 Symposium*, Cleveland, OH, April 1990.

In attempting to reduce costs, the overall management approach may assume as much or more importance as the technologies used. For example, project managers of the Strategic Defense Initiative Organization Delta 180 Project found that "decreasing the burden of oversight and review, and delegating authority to those closest to the technical problems, resulted in meeting a tight launch schedule and reducing overall costs."[24] Determining whether these or similar techniques are appropriate to reducing costs in a high-cost, high-risk robotic or crew-carrying mission would require careful study. However, experience with earlier planetary projects suggests the following maxims for project development:[25] 1) keep the entire project as simple as possible; 2) do as much testing as possible before launch; 3) provide adequate funding reserves for unforeseen problems; 4) avoid complex software and complex internal processes; and 5) keep science payloads to the requirements.

PAYING FOR THE MISSION FROM PLANET EARTH

Returning crews to the Moon and exploring Mars would have a major impact on NASA's yearly budget, and could adversely affect the funding of NASA's other activities. To support the Missions to and from Planet Earth, and the various programs to which NASA has already committed, the Report of the Advisory Committee on the Future of the U.S. Space Program recommended 10-percent real growth in NASA's overall budget over a period sufficient to pay for the Mission from Planet Earth as well as other NASA activities.[26] The National Research Council Committee on Human Exploration of Space recommended growth of NASA's budget by a "few 10ths of percent in GNP."[27] During the years of highest spending on the Apollo program (1964-66) NASA spent about 0.8 percent of the GNP.[28] However, the United States was then in the middle of a "race to the Moon," and beating the Soviet Union to it was a national priority. No such race exists today.

Significant pressures on the discretionary portion of the Federal budget will make obtaining a real growth rate in NASA's budget of 10 percent, or increases of a few tenths percent of the GNP, extremely difficult, unless our national priorities change.[29] NASA's budget submission for fiscal year 1991 included a total of $962.8 million for activities cited in the budget summary as related to SEI. Of that amount, about $188 million was targeted to support new activities.[30] In passing the Appropriations Bill for the Department of Housing and Urban Development and Independent Agencies,[31] Congress deferred consideration of the proposed SEI as a result of "severe budgetary constraints which limit the agency's ability to maintain previously authorized projects and activities."[32] NASA received about $584 million. NASA's budget submission for 1992 contains $94 million in support of identified SEI activities.

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[23] Computing capacity per weight and volume has decreased dramatically over the last 30 years. If existing trends continue, computing capacity may not be a limiting factor.

[24] U.S. Congress, Office of Technology Assessment, *Reducing Launch Operations Costs: New Technologies and Practices*, OTA-TM-ISC-28 (Washington, DC: U.S. Government Printing Office, September 1988), p. 14.

[25] Scott Hubbard, Jet Propulsion Laboratory, personal communication, 1991.

[26] Advisory Committee on the Future of the U.S. Space Program, op. cit., footnote 15, p. 4.

[27] In 1990, NASA's budget was about 0.18 percent of the GNP.

[28] National Research Council, Committee on Human Exploration of Space, op. cit., footnote 5, p. 31.

[29] David Moore, Statement before the Committee on Space, Science, and Technology, U.S. House of Representatives, Jan. 31, 1991.

[30] For fiscal year 1991, NASA placed other ongoing activities in the SEI category to demonstrate that many of its existing activities were already directed toward the goals of SEI.

[31] H.R. 5158, which became Public Law 101-507.

In funding the many elements of the Mission from Planet Earth, or SEI, it will be important to maintain a balance of activities in space. Since the Apollo days, NASA's projects devoted to "manned" activities have received the lion's share of NASA's budget. Recently, that share has increased. In fiscal year 1990, for example, activities for people in space consumed about 70 percent of NASA's budget.[33] Space scientists and other observers of the U.S. space program have raised the concern that the SEI might increase the proportion of funding applied to human activities in space to the detriment of space science, the Mission to Planet Earth and other NASA space projects.[34]

Both the National Research Council's Committee on Human Exploration of Space[35] and the Advisory Committee on the Future of the U.S. Space Program[36] have recommended fencing funding for the rest of NASA's activities from funding for a Mission from Planet Earth. The Advisory Committee specifically recommends "that the civil space science program should have first priority for NASA resources, and continue to be funded at approximately the same percentage of the NASA budget as at present (about 20 percent)."[37] However, the administration and Congress may find it difficult to maintain funding for NASA's base programs if the funding for SEI leads to an even larger percentage of NASA's budget than its endeavors to support people in space now command. Schedule and other delays in such activities would necessarily lead to cost overruns that could "squeeze out" funding for other civilian space activities.

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[32] U.S. House of Representatives, *Conference Report to Accompany H.R. 5158*, Oct. 18, 1990, p. 44. The report went on to say, "It is inevitable in the conduct of the Nation's civil space program that such human exploration of our solar system is inevitable."

[33] Up from about 65 percent in the 2 previous years. U.S. Congress, Office of Technology Assessment, *Access to Space: The Future of the U.S. Space Transportation System*, OTA-ISC-415 (Washington, DC: U.S. Government Printing Office, 1990), p. 5.

[34] Robert L. Park, "After 30 Years of Dreams, a Wake-Up Call for NASA," *The Scientist*, May 27, 1991, pp. 11, 13.

[35] "The committee believes that it is important for the funding support for HEI [SEI] and other major initiatives to continue to be distinct from that for the remainder of the NASA budget, to avoid eroding the base of other essential space and aeronautical capabilities." National Research Council, Committee on Human Exploration of Space, *Human Exploration of Space: A Review of NASA's 90-Day Study and Alternatives* (Washington, DC: National Academy Press, 1990), p. 32.

[36] Advisory Committee on the Future of the U.S. Space Program, op. cit., footnote 15.

[37] Ibid., p. 25.

Chapter 8

International Competition and Cooperation

When the United States was building its civilian space program, political competition with the Soviet Union acted as a goad to enhance U.S. technological capabilities, especially in space. In part, U.S. officials worried that the Soviet Union's successes in launching large spacecraft demonstrated its ability to field ballistic missiles capable of landing nuclear weapons on the United States. The demonstration of U.S. technological leadership by leading in civilian space activities soon became an important part of U.S. motivation for any proposed new activity.[1] In 1961 the Kennedy administration and the 85th Congress took U.S. leadership a step farther by funding a program that soon established across-the-board preeminence in space activities. Not only did the United States demonstrate its preeminence in activities involving human crews, it established strong programs in planetary exploration, meteorological satellites, and land remote sensing. The United States also spearheaded the development of the communications satellite industry, which today is still the only fully commercial space enterprise.[2]

Beginning in the 1970s, other nations, especially Japan and the European countries, have been demonstrating their increasing capabilities in space technology. They are now able to challenge the United States in space applications and in certain areas of space science.[3] As a result, the United States has seen the steady loss of its position as the dominant supplier of space-related goods and services in the world market. Hence, the grounds of competition have shifted away from political competition for global status to economic competition with our traditional allies. America's challenge for the 1990s and beyond will be the construction of effective mechanisms to enhance the U.S. economic position.

Despite the strong competitive foundation, the U.S. space program has also had a long history of encouraging cooperative activities.[4] During the 1960s, the 1970s, and even into the early 1980s, the United States organized cooperative activities — in part to enhance its leadership position. Under those circumstances, most U.S. cooperative efforts were generally unequal partnerships in which the United States could set the foundation and terms of the cooperative venture. In part, the United States could do so because the Soviet Union offered little competition for cooperative programs. The secretive nature of its space program, and the relatively immature level of its technology made the Soviet Union unable to offer much of interest to technologically advanced potential partners.

Although the capacity of the countries of Europe and Japan to challenge U.S. firms means that they will likely continue to gain market share for commercial goods and services, it also means they make more effective partners in cooperative ventures. In some areas of technology other countries lead; hence the United States would gain technologically from cooperating. For most cooperative projects, the combination of skills each party would bring would greatly enhance the project's outcome.

The Soviet Union's continuing experience in supporting a human presence in space on the *Salyut* and *Mir* space stations, in launching a variety of launch vehicles, and its long-term interests in planetary exploration, coupled with much greater openness about its space activities, now make it a potentially attractive partner for cooperative science and technology projects.[5] The Soviet Union is also seeking to attract partners for commercial ventures and is willing to arrange highly competitive terms for such cooperation. The political advantages of competing with the Soviet Union in space have greatly diminished, and are being replaced by a growing realization that cooperation would help support the Soviet Union's transition to a market economy, and assist Soviet political stability as it experiments with democratic reform. On the other hand, the current Soviet economic crisis affects its ability to fund space activities and may make it difficult for Soviet scientists to engage in large cooperative projects.

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[1] Indeed, the role of leadership is codified in the National Aeronautics and Space Act of 1958 (Public Law 85-568). "The aeronautical and space activities of the United States shall be conducted so as to contribute materially to....The preservation of the role of the United States as a leader in aeronautical and space science and technology...(42 U.S.C. 2451, Sec. 102c(5)).

[2] Numerous communications satellites have also been built for civilian government uses.

[3] U.S. Congress, Office of Technology Assessment, *International Cooperation and Competition in U.S. Civilian Space Activities*, OTA-ISC-239 (Washington, DC: U.S. Government Printing Office, 1985), ch. 4.

[4] The National Aeronautics and Space Act of 1958 mandates international cooperation (42 U.S.C. 2451, Sec. 102 c(7)).

As space projects grow in cost and technological complexity, the need for efficient, cost-effective use of resources argues for an international division of labor. During the 1990s, the United States faces the challenge of developing new cooperative mechanisms, based on the new global economic and political realities. That challenge will require U.S. policymakers to alter significantly modes of thinking that derive from the era of the cold war. For example, in future cooperative projects with the United States, Japan and Europe are likely to require increasingly greater voice over the terms of the project. For the Mission from Planet Earth, the United States will have to resolve the apparent tension between its wish to carry out ambitious, and costly, projects on its own and the attraction of seeking foreign participation in order to: 1) reduce costs for each participant, 2) increase overall technological capabilities, 3) expand its opportunities for involvement in wider variety of disciplines, and 4) extend its political influence. The United States will also have to consider the opportunity that cooperation in U.S.-led projects gives for our partners to increase their competitive posture.

COMPETITIVE CONCERNS

How the United States invests in its space program will affect other segments of the economy. Investments made in technologies that could spur industrial development and increase America's international competitiveness would be most welcome in today's economy.[6] As noted earlier, during the 1990s and into the next century, the United States is unlikely to have any competitors in sending human crews to the Moon and Mars. However, we can expect other nations, including Canada, France, Germany, and Japan, to have a strong interest in developing the technologies required for robotics spacecraft and probes. Many of these technologies have a close relationship with increasing productivity in the manufacturing and service sectors.

Although the United States invented robots and still leads in many areas of research, in other countries robotics technologies have assumed a greater role in the economy. Canada, France, Germany, Italy, and Japan,[7] in particular, have targeted automation and robotics (A&R) technologies for development for industrial and governmental use. In some areas, such as manufacturing,[8] their efforts well exceed U.S. capabilities.

Several OTA workshop participants expressed concern that the U.S. space program has not invested adequately in A&R technologies. Canada, France, Germany, and Japan have implemented programs that direct investment on A&R space technologies toward the common goal of supporting their industrial base.

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[5] U.S. Congress, Office of Technology Assessment, *U.S.-Soviet Cooperation in Space*, OTA-TM-STI-27 (Washington, DC: U.S. Government Printing Office, July 1985), ch. 4.

[6] U.S. balance of payments to the rest of the world make the United States the world's greatest debtor nation.

[7] Andrew Tanzer and Ruth Simon, "Why Japan Loves Robots and We Don't," *Forbes*, Apr. 16, 1990, pp. 148-153; William L. Wittaker and Takeo Kanade, *Space Robotics in Japan* (Baltimore, MD: Japanese Technology Evaluation Center, 1991).

[8] See, e.g., the series of articles on the impacts of robotics on manufacturing in the special issue of *Technological Forecasting and Social Change*, vol. 35, April 1989.

Canada

Canada has used its involvement in the space shuttle system, for which it provided the Canada Arm, and the space station, for which it is providing the Mobile Servicing System and Special Purpose Dextrous Manipulator, to build its capabilities in A&R. The Canadian A&R program has three integrated elements that are focused toward one common goal: the development and implementation of the robotic system for space station *Freedom*.[9] They are divided into three phases:

- *Near Term (baseline)* — Mobile Servicing System and Special Purpose Dextrous Manipulator. Canadian objectives include the development and implementation of a robotic system that will meet the baseline requirements for the space station during assembly, maintenance, and operations.
- *Mid Term* — Advanced Technology Program. Canadian objectives include the enhancement of the basic robotic system with higher performance capabilities to support its future growth. Examples of such technologies include real time collision prevention and avoidance, and advanced vision. The additional capability should lead to reduced costs and increased crew productivity.
- *Far Term* — Strategic Technologies in Automation and Robotics. Canadian objectives include: 1) the development of strategically important A&R technologies for potential incorporation into the Canadian Mobile Servicing System over its lifetime by contracting out research to industry; and 2) the support of national economic development through encouraging commercialization of the developed technologies.

Photo credit: National Aeronautics and Space Administration

Repair of the Solar Maximum spacecraft aboard space shuttle *Challenger*, April 11, 1984. The Canadian remote manipulator arm was used to maneuver astronauts into position for their repair tasks.

Europe

Germany, Italy, and France have expressed considerable interest in developing robotics technology for use in space. For example, the German Aerospace Research Establishment (DLR) is building the Space Robot Technology Experiment, ROTEX, which will fly in the next German Spacelab mission (D-2) aboard the space shuttle, scheduled for 1992. ROTEX is a small, six-axis robot that will be used to verify an array of robotic tasks in space. It is designed to perform a variety of preprogrammed tasks, but also under control of astronauts and by remote control from Earth, using 3-dimensional stereo computer graphics and stereo television. ROTEX will:[10]

- verify joint control under microgravity;
- demonstrate and verify the use of ROTEX handcontrollers;

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[9] NASA Advanced Technology Advisory Committee, "Advancing Automation and Robotics Technolgy for the Space Station *Freedom* and for the U.S. Economy," Technical Memorandum 103851 (Moffett Field, CA:Ames Research Center, National Aeronautics and Space Administration, May 1991), app. C.

[10] G. Hirzinger, J. Dietrich, and B. Brunner, "Multisensory Telerobotic Concepts for Space and Underwater Applications," *Proceedings of the Space and Sea Colloquium*, European Space Agency, Paris, France, Sept. 24-26, 1990, pp. 151-61.

- demonstrate and verify the use of human-machine interfaces that also allow for teleoperation from Earth; and
- verify the execution of a variety of tasks in space, e.g., making plug-in connections, assembly, and catching free-flying objects.

DLR is also working on lightweight robots and on a variety of A&R methods to increase productivity in space. It expects many of these methods to have Earthbound applications.

Robotics experts at the French space agency, Centre National D'Etudes Spatiales (CNES), are exploring the potential for an "automatic planetary rover," and have established partnerships with other French laboratories working on both terrestrial and undersea mobile robots.[11] The program is in its early stages and is focused on developing robotic devices for scientific exploration of Mars: sample analysis, establishment of geophysical profiles, and deployment of autonomous stations, for possible Mars deployment in A.D. 2000.

Japan[12]

Japan has especially targeted A&R for research & development investment, as it expects these technologies to provide increased productivity in a variety of areas. It also expects to reduce its operations costs for crew-carrying missions by employing A&R technologies, as well as create A&R devices for robotic missions. The National Space Development Agency (NASDA) funds the Space Robot Forum, a group that brings together members from government, industry, and academia to recommend directions for space robotics. It has urged the development and extensive use of so-called third-generation robotics systems that operate with little human intervention.[13]

Japan is developing a first-generation, 9.7-meter-long robot arm for use with its Japan Experimental Module (JEM) for the international space station *Freedom*. It will carry a smaller arm and gripper at the end to provide greater dexterity. The Forum has suggested developing a space station in the 21st century that would be operated by robots controlled from Earth.

Japan has also expressed interest in exploring the Moon and exploiting lunar resources. Individuals at the Japanese space agency, NASDA, have examined the potential for developing a lunar base, using lunar materials for construction.[14]

COOPERATIVE OPPORTUNITIES

As noted in an earlier OTA report, "U.S. cooperative space projects continue to serve important political goals of supporting global economic growth and open access to information, and increasing U.S. prestige by expanding the visibility of U.S. technological accomplishments."[15] A return to the Moon and an exploration of Mars present a range of possible cooperative activities with other nations. Because the costs for intense planetary exploration are likely to be very high, international cooperative activities could reduce U.S. costs and increase the U.S. return on its investment for exploration. A well-conceived cooperative program could also establish the United States as a leader in exploration.[16] A broadly based cooperative exploration program with varied levels of participation, whether it was primarily robotic or employed human crews, would also enable the United States to encourage less developed countries to enhance their own science and technology base. However, cooperative projects must be carefully structured to keep costs within bounds. Otherwise, the numerous mangagement interfaces and the differences in cultures may vastly increase total costs for a project.[17]

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[11] Denis J.P. Moura, "Automatic Planetary Rover: The French Mars and Lunar Rover Preparatory Program," CNES briefing charts, March 1991.

[12] William L. Wittaker and Takeo Kanade, *Space Robotics in Japan* (Baltimore, MD: Japanese Technology Evaluation Center, 1991).

[13] First-generation robotic devices would work largely by teleoperation. Second-generation devices are those that do simple tasks on their own; third generation robotic devices would be nearly autonomous. William L. Wittaker and Takeo Kanade, "Japan Robotics Aim for Unmanned Space Exploration," *IEEE Spectrum*, December 1990, p. 64.

[14] T. Iwata, "Technical Strategies for Lunar Manufacturing," IAA-88-588, Presented at the 39th Congress of the International Astronautical Federation Meeting, Bangalore, India, Oct. 8-15, 1988.

[15] U.S. Congress, Office of Technology Assessment, *International Cooperation and Competition in Civilian Space Activities*, op. cit., footnote 3, p. 7.

[16] John M. Logsdon, "Leading Through Cooperation," *Issues in Science and Technology*, summer 1988, pp. 43-47.

In the past, most of the National Aeronautics and Space Administration's (NASA) cooperative activities have been bilateral, in large part because bilateral cooperation is much simpler and therefore less costly to manage than multilateral cooperation.[18] They have also generally been bounded in time. Yet increasingly the size and duration of projects have led to the need for a more flexible position. While some projects are appropriate for a bilateral approach, others, because of their size, complexity, or duration, may require a multilateral approach.

Even if, for international legal purposes, the individual agreements are better arranged between pairs of nations, the day-to-day interactions are likely to be multilateral, rather than bilateral in scope. For example, although the agreements of the United States with Canada, the European Space Agency (ESA), and Japan concerning *Freedom* are bilateral agreements, in designing, building, and operating the space station, representatives of the four parties must meet and coordinate with each other primarily as a group in order to carry out their business most efficiently. Hubble Space Telescope also requires continuing management interaction among the nations involved.[19]

The need for a broader level of cooperation has led to several suggestions for an umbrella organization or mechanism to coordinate and manage large, international space projects.[20] Such suggestions have always had to face the concern that the ensuing bureaucratic arrangements could become extremely complicated and that individual nations could begin to lose control over their own projects. They could also lead to high overall program costs related to need to involve more organizations, each with its own agenda and scientific goals, in the process. The multilateral Inter-Agency Consultative Group (IACG) has been suggested as a possible model for future cooperative ventures because it was able to circumvent these drawbacks.[21]

Prior to the passage of Comet Halley through the inner solar system in 1986, the ESA, Japan, the Soviet Union, and the United States formed the IACG to coordinate their efforts to observe Comet Halley from space (box 8-A). The IACG organization was deliberately kept informal and simple in order to minimize bureaucratic impediments and to focus on scientific tasks. It operated on the understanding that the IACG would serve only in an advisory capacity to the member agencies. In addition, there would be no exchange of funds and minimal technology transfer.[22]

The IACG provides an attractive model because it is relatively simple, and because it scored a major success in the Halley encounter. Each cooperating entity brought a particular strength to the joint project in the form of a spacecraft or

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[17] The fate of the Mars Observer Visual and Infrared Mapping Spectrometer is particularly instructive. Removed from the Mars Observer payload in order to save money, it was later resurrected to fly on the Soviet Mars '94 mission as a joint U.S./Soviet/French/Italian effort. It became overly complicated and the U.S. financial share of the project eventually grew greater than the original instrument would have cost on Mars Observer. The United States eventually had to cancel its involvement, deeply disappointing U.S. scientists and international partners alike. Steven Squyres, Cornell University, 1991.

[18] "NASA prefers bilateral relations over projects that might involve three or more countries or organizations." U.S. Congress, Office of Technology Assessment, *UNISPACE '82: A Context for International Cooperation and Competition*, OTA-TM-ISC-26 (Washington, DC: U.S. Government Printing Office, March 1983), p. 68.

[19] Joan Johnson-Freese, *Changing Patterns of International Cooperation in Space* (Malabar, FL: Orbit Book Co., 1990), ch. 9.

[20] Ibid.

[21] Kenneth S. Pedersen, "The Global Context: Changes and Challenges," *Economics and Technology in U.S. Space Policy*, Molly Macauley (ed.) (Washington, DC: Resources for the Future, 1986), pp. 173-198.

[22] Joan Johnson-Freese, *Changing Patterns of International Cooperation in Space* (Malabar, FL: Orbit Book Co., 1990), ch. 15.

Box 8-A—The Inter-Agency Consultative Group (IACG)

Delegates from the European Space Agency (ESA), Japan, the Soviet Union, and the United States met in Padua, Italy, in 1981 to discuss ways of coordinating their efforts to observe Comet Halley from space. E.A. Trendelenburg, director of scientific programs for ESA, and Roald Sagdeev, director of the Space Research Institute of the Soviet Union had earlier urged that those nations with Comet Halley projects could maximize their scientific return by working directly together rather than through a broad-based organization, such as the International Committee on Space Research (COSPAR). Other officials agreed and formed the IACG to coordinate their efforts to observe Comet Halley from space.

The IACG's initial meeting resulted in three working groups that met as often as necessary to generate recommendations related to the flight projects and to allocate specific tasks before, during, or following the Halley encounter. Although the United States sent no probe to the comet, in cooperation with the International Halley Watch, it provided critical positional data on the Comet and the space probes. In order to give the European Giotto space probe the best possible chance to image the nucleus of Halley, accurate observations of both the comet and the probe were necessary. The United States used the Deep Space Network to track the two Soviet Venera probes as they passed by Halley on March 6 and 9, 1986, on their way to Venus.[1] The resulting observations enabled scientists to reduce considerably the positional uncertainty of the comet's path, and made it possible to guide ESA's Giotto accurately into the outer part of Comet Halley. Representatives from all organizations involved met regularly to coordinate their activities, yet the United States at that point had no formal cooperative agreement with the Soviet Union.[2]

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[1] This was called the Pathfinder concept.

[2] Indeed, Roald Sagdeev, former director of the Soviet Institute of Space Sciences, once quipped that "during the Halley observations, the United States acted as subcontractor to the European Space Agency" in supplying data about Venera's position.

SOURCE: Joan Johnson-Freese, *Changing Patterns of International Cooperation in Space* (Malabar, FL: Orbit Book Co., 1990), ch. 15.

equivalent capability; the result from the whole was much greater than the sum of its individual parts. The IACG, which began as an experiment, is continuing and will focus on cooperating in space science. One of the reasons it worked well is that cooperative ventures with few interfaces are much easier to arrange and manage.

The United States might wish to cooperate on a wide variety of projects related to the exploration of the Moon and Mars.[23] The extent to which the IACG or an organization modeled after it would be successful for such purpose, would depend in part on whether it could maintain simplified management interfaces. Of greater importance is the question of who the potential partners might be.

At the present time, the only countries to demonstrate a strong interest in sending human crews to Mars are the United States and the Soviet Union. No other country has the launch vehicles or other infrastructure necessary to land crews on the Moon. In large part, they have not invested in the means to launch and support human crews because other countries have different economic and political goals. However, Japan has an active program to study the Moon with robotic instruments,[24] and European scientists within ESA have studied the scientific opportunities for exploring Mars[25] and the Moon.[26] The Soviet Union is planning a robotic exploratory mission to Mars in 1994 and considering a later sample return mission to Mars. The Soviet missions are aimed in part at preparing the way to send humans to Mars sometime in the next century. The Soviet Union has for years contemplated launching a lunar orbiter[27] and has studied the potential for returning a lunar sample from the farside of the Moon, but has no mission under planning. Hence, based on demonstrated interest, the strongest opportunities for the United States to initiate cooperative projects for at least the next decade would be on robotic ones. All three major entities—ESA, Japan, and the Soviet Union might be interested in participating.

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[23] Bruce C. Murray, "Can Space Exploration Survive the End of the Cold War?" *The Planetary Report*, May/June 1991.

[24] Shigebumi Saito, "Japan's Space Policy," *Space Policy*, August 1989, pp. 193-200.

[25] European Space Agency, *Mission to Mars: Report of the Mars Exploration Study Team* (Paris, France: European Space Agency, January 1990).

[26] The European Space Agency report is now in progress.

During the early part of the next century, cooperation with the Soviet Union on sending human crews to and from Mars might also be attractive,[28] if the Soviet Union can survive its current economic and political crises,[29] and the United States can resolve its own economic difficulties. Given the high costs of supporting human crews in space and Japan's and ESA's experience with space station *Freedom*, Japan and the European countries might be highly resistive to such cooperation for many years.[30]

The following examples illustrate the range of potential projects that might be possible:

- *Life sciences research* — Cooperating on life sciences work with the Soviets could be highly fruitful for both parties. Soviet scientists have collected considerable data on the reactions of humans to the space environment.[31] However, in the past they were reluctant to share life sciences data, in part, because the data were considered militarily sensitive. Soviet scientists are now able to share more of their data on weightlessness and other life sciences issues. NASA is now cooperating with the Soviet Union in a variety of life sciences areas, including standardization of measurements, use of U.S. equipment on board *Mir*, and exchange of biological specimens.[32] The two countries could extend their opportunities to collect high-quality long- and short-term reactions to the space environment by agreeing to fly astronauts and cosmonauts on each others' space vehicles.
- *Astronomy from the Moon* — Making astronomical observations from the Moon might be an especially fruitful area in which to cooperate, at a variety of levels. The major space-faring nations also have strong programs in astronomy and would likely have an interest in cooperating on designing and placing observatories of various sizes on the Moon. In order to keep initial efforts as simple as possible, it might be possible for each participating entity to design and build its own telescope, each with different capabilities. Such a program could even involve countries that lack an independent means to reach the Moon. For example, it could involve countries of Eastern Europe that have the scientific expertise to do serious astronomical research but lack the rockets and money to launch their telescopes.
- *Small rovers on the Moon or Mars* — Several small rovers could be sent on a single launch. In a cooperative program, each cooperating entity could build its own small rover, perhaps specialized to gather specific data. Here again, each country could con-

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[27] Nicholas L. Johnson, *The Soviet Year in Space 1990* (Colorado Springs, CO: Teledyne Brown Engineering, February 1991), pp. 123-124.

[28] "Senior Soviet Space Officials Outline Plan for Joint Mars Mission," *Aviation Week and Space Technology*, Nov. 19, 1990, p. 67; Burton I. Edelson and John L. McLucas, "U.S. and Soviet Planetary Exploration: The Next Step is Mars, Together," *Space Policy*, November 1988, pp. 337-349.

[29] "Aggressive Soviet Space Program Threatened by Budget, Policy Changes," *Aviation Week and Space Technology*, Mar. 18, 1991, pp. 153-154.

[30] The many delays and restructuring of space station *Freedom* have angered our partners.

[31] A.D. Egorov, A.I. Grigoriev, and V.V. Bogomolov, "Medical Support on Mir," *Space*, vol. 7, No. 2, April/May 1991, pp. 27-29.

[32] A 1987 agreement established a Joint Working Group in Space Biology and Medicine, which shares data acquired on Mir and the Space Shuttle.

tribute according to its own capabilities. If one small rover failed, its failure would not interfere with the ability of the others to succeed.

- *Use of Soviet Energia* — As Western experience with the Soviet space program grows and confidence improves, the United States could envision closer cooperation with the Soviet Union. For example, the Soviet Union possesses the world's only heavy-lift launch vehicle, capable of lifting about 250,000 pounds to low-Earth orbit. It has offered to make *Energia* available to the United States for launching large payloads. In the near term, the Soviet offer could assist in developing U.S. plans to launch large, heavy payloads, e.g., fuel or other noncritical components of a Moon or Mars expedition. If these cooperative ventures succeeded, they could be extended to include the use of Energia to launch other payloads, perhaps even a joint mission to the Moon or Mars.

- *Cooperative network projects* — Europe and the United States are both exploring the use of instrumental networks on Mars to conduct scientific exploration. Each cooperating entity could contribute science payloads, landers, or orbiting satellites to gather data for a joint network project.

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